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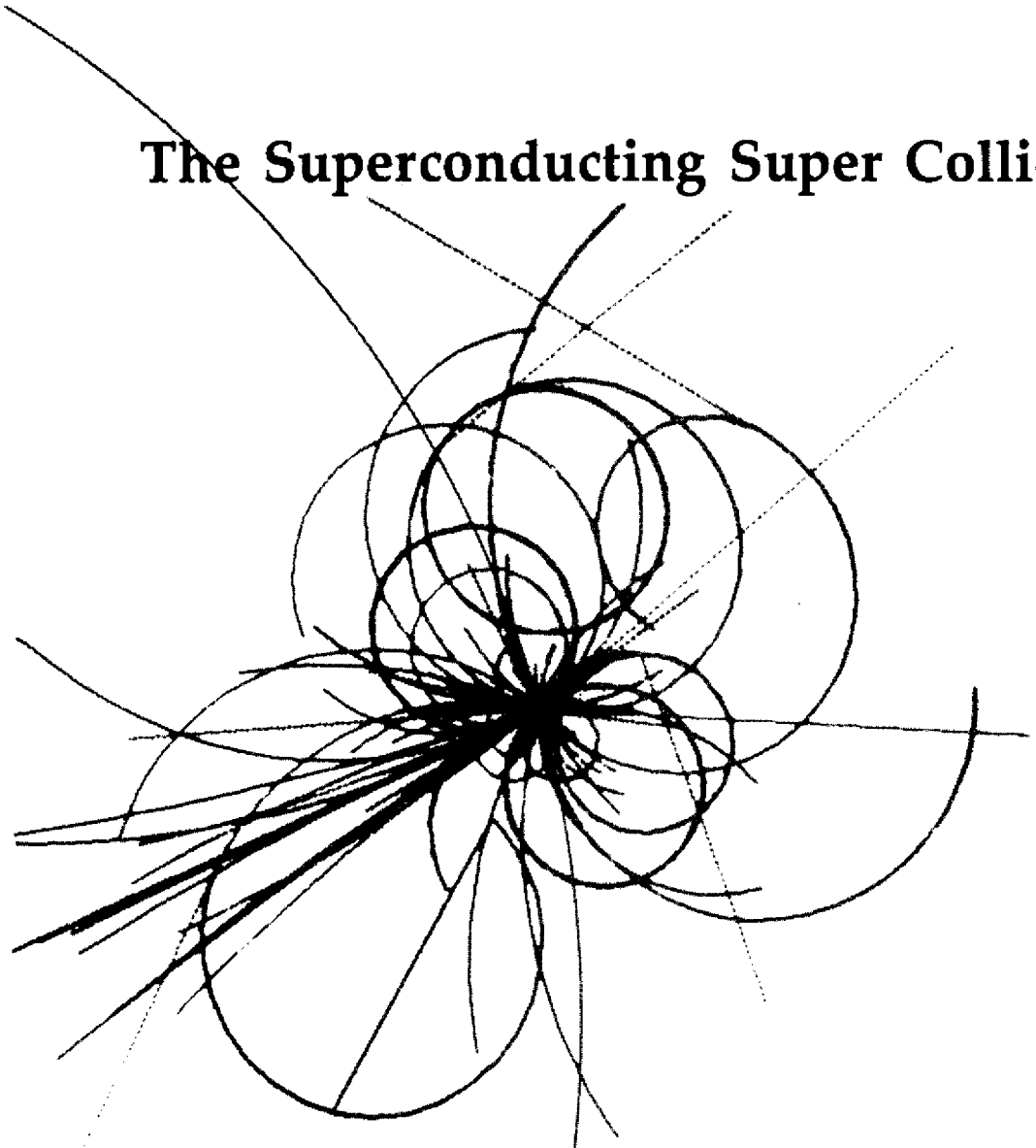

General Formulas for the Adiabatic Propagation Velocity of the Normal Zone

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GENERAL FORMULAS FOR THE ADIABATIC PROPAGATION VELOCITY OF THE NORMAL ZONE*

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Abstract

The influence on the propagation velocity of the normal zone of four phenomena was investigated: 1) The temperature dependence of the specific heat and the thermal conductivity, 2) The current-sharing zone, 3) The electromagnetic diffusion of current through a possible super-stabilizer, and 4) The thermal diffusion through a possible insulator. At the beginning, these influences were studied independently of each other. In all cases, after creating a model of the particular phenomenon, the equations of thermal and electromagnetic behavior were solved analytically and the expressions for the propagation velocity obtained. These expressions were then put into nondimensional forms, which have allowed us to define four correction factors taking into account the studied influences, depending only on one or two nondimensional parameters. Subsequent studies were made to investigate how to combine these correction factors in order to obtain general formulas for the velocity, taking into account a part or all of these influences. A review is presented here of these formulas, which are of interest for the superconducting windings, where the heat transfer to helium can be neglected on the time scale of the quench process.

Introduction

Hypothesis of adiabaticity

The study of the propagation of the normal zone along the superconducting windings has already been the object of many publications.[1-33] However, all these publications have one point in common: they are all concerned with conductors immersed in helium baths, and their authors direct their efforts primarily toward modelization, calculation, and measurement of thermal exchanges between the conductors and the helium.

In this study we are more specifically interested in indirectly-cooled magnets, such as the layer of conductors representative of the ALEPH solenoid[34] presented in Figure 1.

In this configuration, the annular ring and especially the layer of insulation (between the annular ring and the layer of conductors) introduce important thermal resistance. In more precise terms, a characteristic time τ_4 of thermal diffusion across the width L_4 of the layer insulation is given by:

$$\tau_4 = \frac{L_4^2}{D_4} \qquad (s) \qquad (1)$$

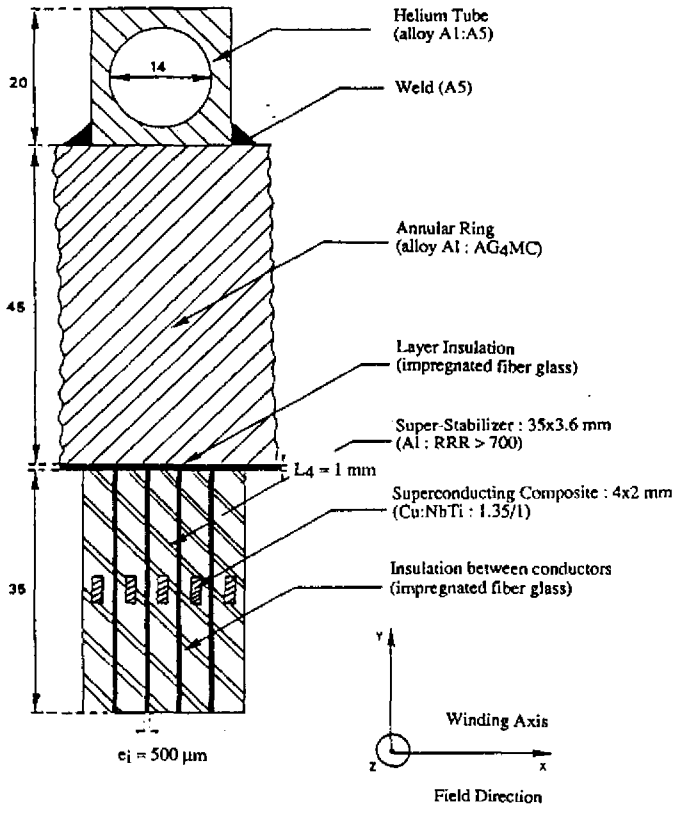

Figure 1. Cut away view of the ALEPH solenoid.

where D_4 is the thermal diffusivity of the layer insulation (m^2s^{-1}). Typically:

$$D_4 = 10^{-6}\, m^2s^{-1} \qquad L_4 = 10^{-3} m$$

Hence: $\tau_4 = 1s$

In addition, a characteristic time τ_p of the propagation phenomenon is given by:

$$\tau_p = \frac{D_t}{v^2} \qquad (s) \qquad (2)$$

where D_t is the equivalent longitudinal thermal diffusivity of the elementary winding pattern (m^2s^{-1}) and v is the longitudinal propagation velocity (ms^{-1}). Typically:

$$D_t = 0.1\, m^2s^{-1} \quad v = 10\, ms^{-1}$$

Hence: $\tau_p = 10^{-3}\, s$

It appears that τ_p is small in comparison to τ_4. During τ_p the thermal diffusion will be limited to a small width of the layer insulation. What follows in particular is that at the scale of propagation, the heat flux transferred to the annular ring and to the helium is negligible.

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Consequently, we see that the layer of insulated conductors—or, as the case may be, the elementary winding pattern—is thermally decoupled from the exterior and thus shows *an ideally adiabatic behavior.*

Adiabatic propagation velocity, with but one exception,[35] has only been regarded, in terms of theory, as a limiting case of the propagation velocity when immersed in a helium bath, with the coefficient of exchange with helium tending towards zero.[1, 2, 28]

Different aspects of the problem

A complete study of the propagation of the normal zone along the layer of conductors of Figure 1 must take into account the following four influences:

- *Influence of the current-sharing zone*
- *Influence of the temperature dependence of the specific heat and of the thermal conductivity of materials.*
- *Influence of electromagnetic diffusion in the super-stabilizer.* In effect, the conductor used by the ALEPH solenoid consists of a conventional multi-filament composite enclosed in a large section of aluminum. When such a conductor switches to the normal resistive state, the current, initially confined to the composite, needs a certain amount of time to be diffused in the super-stabilizer. The propagation front thus carries with it a wake of electromagnetic diffusion along which the dissipated power density per unit volume varies. Thus the question is posed of the role played by this power in calculating propagation velocity.
- *Influence of thermal diffusion in the layer insulation.* During a transition of the layer of conductors in Figure 1, most of the dissipated power serves to heat the conductor and to make it switch to the normal resistive state and the residue is transferred to the layer of insulation. As we have described in Section I.1, given the weak thermal conductivity of the insulator, the heat, like the current, needs a certain amount of time to be diffused in the insulation. The propagation front carries with it a wake of thermal diffusion. Thus the question is likewise posed of the role played by the insulation layer in calculating propagation velocity.

Method

The above review of influences on propagation velocity shows that the latter is a blend of thermal and electromagnetic phenomena, mainly non-linear, and that these phenomena occur on different scales. The difference between scales renders all numerical approaches to the problem difficult. We have thus adopted an entirely different method of which we present here the principal results. This method consists, first, of a study of each of the aspects of the problem independently from each other, and, second, of an attempt to reconstitute the mechanics of the entirety. Sections II-V present the conclusions of the studies of each of the previously described influences. In each case, we have analytically solved the equations of thermal and electromagnetic behavior and we have established an implicit equation for propagation velocity. This implicit equation was then put into dimensionless form, which has allowed the reduction of the numerous related parameters to one or two, as the case may be. It is this dimensionless form that we present here. In Section VI, we finally show how to combine these parameters to estimate the propagation velocity along the layer of conductors in Figure 1. The details of all these studies can be found in Reference 36.

Influence of the current-sharing zone

Let us consider the current-sharing phenomenon. First, we introduce an average power density per unit volume P_j, variable in relation to temperature T, and defined[37] by:

$$\begin{cases} P_j = 0 & \forall T, T \le T_{ci} \\ P_j = P_{jt}\dfrac{T - T_{ci}}{T_c - T_{ci}} & \forall T, T_{ci} \le T < T_c \\ P_j = P_{jt} & \forall T, T_c \le T \end{cases} \qquad (3)$$

where:

T_c is the critical temperature at the given field and zero current (K).

T_{ci} is the critical temperature at the given field and the given current (K).

P_{jt} is the average power density per unit volume dissipated by the elementary winding pattern in the normal resistive state (Wm^{-3}).

Let us call the dimensionless parameter m_I the *current-sharing parameter*, defined by:

$$m_I = 4\,\frac{\Delta H_s}{\Delta H_i} \qquad \text{(dimensionless)} \qquad (4)$$

where:

ΔH_s is the variation between T_0 and T_{ci} of the enthalpy per unit volume of the elementary winding pattern (Jm^{-3}).
ΔH_i is the variation between T_{ci} and T_c of the enthalpy per unit volume of the elementary winding pattern (Jm^{-3}).

T_0 is the operating temperature (K)

We thus establish, for all values of m_I, the existence of a constant-velocity asymptotic shift of the temperature profile, for which the velocity v is given by:

$$v = v_I(m_I)\sqrt{\frac{D_t}{P_{jt}\Delta H_t}} \qquad (ms^{-1}) \qquad (5)$$

where:

ΔH_t is the variation between T_0 and $T_t = (T_c + T_{ci})/2$ of the enthalpy per unit volume of the elementary winding pattern (Jm^{-3}).

D_t is the equivalent longitudinal thermal diffusivity of the elementary winding pattern, at T_t (m^2s^{-1}).

v_I is the current-sharing corrective factor, determined versus m_I by the system of equations:

$$\begin{cases} \sin\left[\sqrt{\frac{m_I+2}{v_I^2}-1}\,\ln\left(\frac{m_I+2}{m_I v_I^2}\right)\right] = \frac{2v_I^2}{m_I+2}\sqrt{\frac{m_I+2}{v_I^2}-1} \\ \cos\left[\sqrt{\frac{m_I+2}{v_I^2}-1}\,\ln\left(\frac{m_I+2}{m_I v_I^2}\right)\right] = 1-\frac{2v_I^2}{m_I+2} \\ 0 \le \sqrt{\frac{m_I+2}{v_I^2}-1}\,\ln\left(\frac{m_I+2}{m_I v_I^2}\right) \le \pi \end{cases} \qquad (6)$$

The curve $v_I = f(m_I)$ is presented in Figure 2.

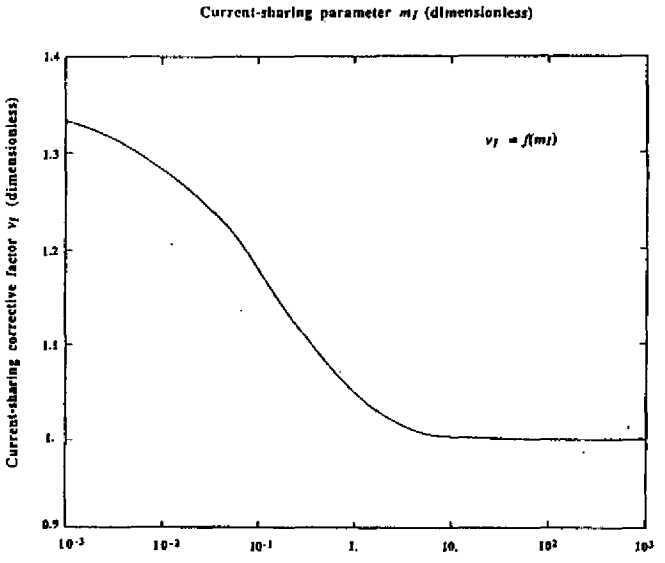

Figure 2. Curve $v_I = f(m_I)$

Influence of the temperature dependence of physical characteristics

Let us consider the temperature dependence of the characteristics of the elementary winding pattern. First, we introduce a specific heat C_t and a thermal conductivity k_t, variables in relation to T and defined[38] by:

$$C_t = \beta_t T^3 + \gamma_t T$$

$$k_t = \kappa_t T \qquad (7)$$

where β_t, γ_t, and κ_t are real, positive constants, determined so as to obtain the best approximation of the real curves $C_t = f(T)$ and $k_t = f(T)$ alongside T_t.

Let us call the dimensionless parameter m_{II} the *temperature dependence parameter*, defined by:

$$m_{II} = \frac{4\beta_t T_t^2\,\Delta H_t}{C_t(T_t)^2} \qquad \text{(dimensionless)} \qquad (8)$$

where $C_t(T_t)$ is the specific heat per unit volume of the elementary winding pattern at T_t ($Jm^{-3}K^{-1}$).

We thus establish, for all values of m_{II} ($0 \le m_{II} \le 1$), the existence of a constant-velocity asymptotic shift of the temperature profile, for which the velocity v_{II} is given by:

$$v_{II} = v_{II}(m_{II})\sqrt{\frac{D_t P_{jt}}{\Delta H_t}} \qquad (ms^{-1}) \qquad (9)$$

where v_{II} is the temperature-dependence corrective factor determined versus m_{II} by the implicit equation:

$$\frac{K_{1/3}\left[\frac{1}{3}\frac{(1-m_{II})^{3/2}}{m_{II}}v_{II}^2\right]}{K_{2/3}\left[\frac{1}{3}\frac{(1-m_{II})^{3/2}}{m_{II}}v_{II}^2\right]} = \sqrt{1-m_{II}} \qquad (10)$$

K_ξ being the modified Bessel function of the second kind and of order ξ.

The curve $v_{II} = f(m_{II})$ is presented in Figure 3.

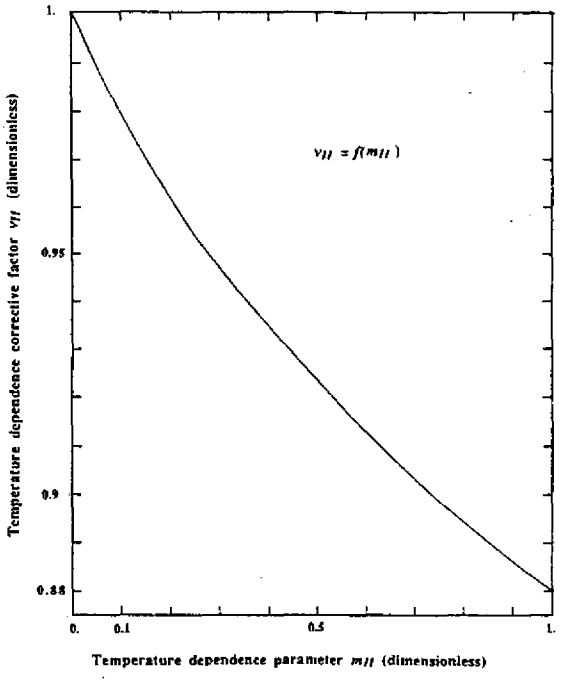

Figure 3. Curve $v_{II} = f(m_{II})$

Influence of electromagnetic diffusion in the super-stabilizer

The model we have developed in order to examine this influence is presented in Reference 39; here we are satisfied with a reexamination of the principal results, generalized to any conductor geometry.

Let us call the dimensionless parameter m_{III} the *first super-stabilization parameter*, defined by:

$$m_{III} = \frac{\rho_2 A_1}{\rho_1 A_2} \qquad \text{(dimensionless)} \qquad (11)$$

where:

ρ_1 (ρ_2 respectively) is the equivalent longitudinal resistivity of the composite in the normal resistive state (of the super-stabilizer, respectively)(Ωm).

A_1 (A_2 respectively) is the composite section (the super-stabilizer, respectively)(m^2).

A criterion of super-stabilization is given by:

$$m_{III} << 1 \qquad (12)$$

Let us call the dimensionless parameter p_{III} the *second super-stabilization parameter*, defined by:

$$p_{III} = \frac{v_0 L_{2e}}{D_e} \qquad \text{(dimensionless)} \qquad (13)$$

where:

L_{2e} is the equivalent depth of the super-stabilizer defined by:

$$L_{2e} = \frac{A_2}{P_d} \qquad (m) \qquad (14)$$

P_d is the composite perimeter in contact with the super-stabilizer (m).

D_e is the equivalent diffusivity defined by:

$$D_e = \sqrt{2 D_m D_t} \qquad (m^2 s^{-1}) \qquad (15)$$

$Dm = \frac{\rho_2}{\mu_0}$ is the electromagnetic diffusivity of the super-stabilizer ($m_2 s^{-1}$).

v_0 is the propagation velocity calculated assuming that the current remains confined to the composite:

$$v_0 = \sqrt{\frac{D_t P_{j0}}{\Delta H_t}} \qquad (ms^{-1}) \qquad (16)$$

P_{j0} is the average power density per unit volume dissipated by the elementary winding pattern assuming that the current is confined to the composite in the normal resistive state (Wm^{-3}).

We thus establish, for all parameter values, the existence of a constant-velocity asymptotic shift of the temperature profile and of the magnetic induction profile, for which the velocity v_{III} is given by:

$$v_{III} = \nu_{III}\, v_0 \qquad (ms^{-1}) \qquad (17)$$

where ν_{III} is the super-stabilization corrective factor, for which the result changes depending of the geometry studied.

For a layer of conductors such as that presented in Figure 1, ν_{III} is determined versus m_{III} and p_{III} by the implicit equation:

$$\nu_{III} = \frac{m_{III} p_{III}}{\tanh(p_{III}\nu_{III}) + m_{III} p_{III} \nu_{III}} \qquad (18)$$

Curves of $\nu_{III} = f(m_{III}, p_{III})$ are presented in Figure 4.

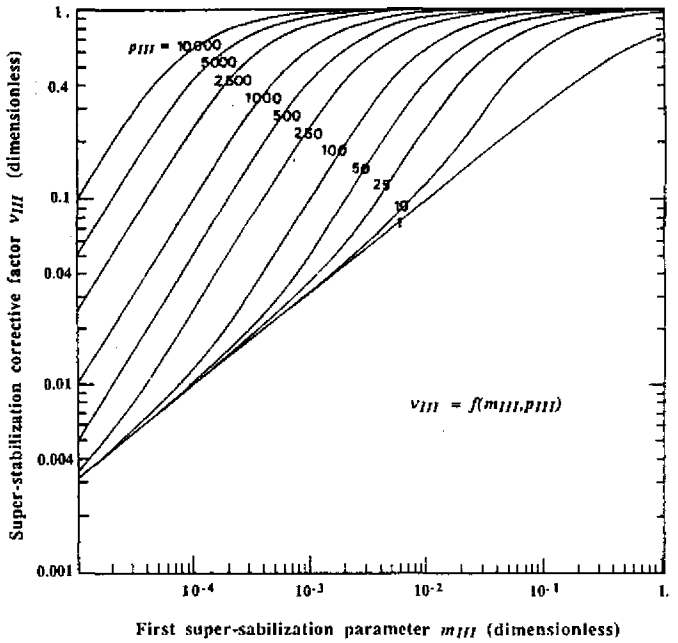

Figure 4. Curve $\nu_{III} = f(m_{III} p_{III})$

Influence of thermal diffusion in the layer insulation

General features

In a layer of conductors such as that in Figure 1, we distinguish two types of insulation: the insulation between conductors, of typical width $e_i = 100\ \mu m$, and the layer insulation, which surrounds the layer of conductors. A characteristic time of thermal diffusion in the insulation between conductors is given by:

$$\tau_i = \frac{e_i^2}{D_4} = 10\ ms \qquad (19)$$

It seems therefore that τ_i is of the same order as τ_p, but is smaller than τ_4, where τ_p and τ_4 are the characteristic times previously defined. During τ_p, the heat is thus largely diffused in the insulation between conductors, but only penetrates a small portion of the layer insulation. For the calculation of velocity, we therefore suppose that temperature is constant through each cross-section of the system (conductor and insulation between conductors), which we regard as a homogeneous, isotropic medium.

In the following, we designate by medium 3 the system (conductor and insulation between conductors) and by medium 4 the layer insulation. We have conducted a separate study for the layers of insulated super-stabilized conductors, in which both electromagnetic and thermal diffusion phenomena interfere.

Case of a layer of insulated multi-filament superconductive composites

Let us call the dimensionless parameter m_{IV} the *first insulation parameter*, defined by:

$$m_{IV} = \sqrt{\frac{k_4 C_4}{k_3 C_3}}\ \frac{D_3}{v_0 L_3} \qquad \text{(dimensionless)} \qquad (20)$$

where:

C_3 (C_4 respectively) is the equivalent specific heat per unit volume of medium 3 (medium 4 respectively) at T_t ($Jm^{-3}K^{-1}$).

k_3 (k_4 respectively) is the equivalent longitudinal thermal diffusivity of medium 3 (medium 4 respectively) at T_t ($Wm^{-1}K^{-1}$).

$D_3 = k_3/C_3$ (L_3 respectively) is the equivalent longitudinal thermal diffusivity (half-width, respectively) of medium 3.

v_0 is the propagation velocity calculated assuming that the layer of conductors is bare (without layer insulation):

$$v_0 = \sqrt{\frac{D_3 P_{j0}}{\Delta H_3}} \qquad (ms^{-1}) \qquad (21)$$

P_{j0} is the average power density per unit volume dissipated by the elementary winding pattern without the layer insulation (Wm^{-3}).

ΔH_3 is the variation between T_0 and T_t of the enthalpy per unit volume of medium 3 (Jm^{-3}).

Let us call the dimensionless parameter p_{IV} the *second insulation parameter*, defined by:

$$p_{IV} = \frac{v_0 L_4}{\sqrt{D_3 D_4}} \qquad \text{(dimensionless)} \qquad (22)$$

where $D_4 = k_4/C_4$ (L_4 respectively) is the thermal diffusivity (the width, respectively) of medium 4.

We thus establish, for all values of m_{IV} and of p_{IV}, the existence of a constant-velocity asymptotic shift of the temperature profile, for which the velocity v_{IV} is given by:

$$v_{IV} = \frac{\nu_{IV}}{\sqrt{1 + m_{IV}\dfrac{\tanh(p_{IV}\,\nu_{IV})}{\nu_{IV}}}}\, v_0 \qquad (ms^{-1}) \qquad (23)$$

where ν_{IV} is the insulation corrective factor, determined versus m_{IV} and p_{IV} by the implicit equation:

$$\tanh^2(p_{IV}\,\nu_{IV}) + 3\frac{\tanh(p_{IV}\,\nu_{IV})}{p_{IV}\,\nu_{IV}} + \left[\frac{2}{m_{IV}p_{IV}} - 1\right] = \frac{2}{m_{IV}p_{IV}\nu_{IV}^2} \qquad (24)$$

Curves of $\nu_{IV} = f(m_{IV}, p_{IV})$ are presented in Figure 5.

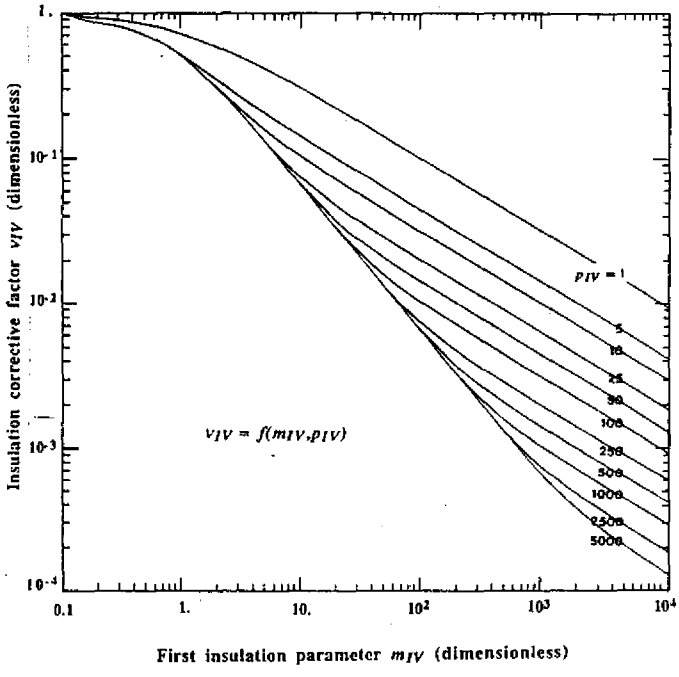

Figure 5. Curve $\nu_{IV} = f(m_{IV} p_{IV})$

Case of a layer of insulated super-stabilized conductors

We designate by medium 1 the multi-filament superconductive composite, by medium 2 the super-stabilizer, by medium 3 the system {composite + super-stabilizer + insulation between conductors}, and by medium 4 the layer insulation.

Let us reintroduce the parameters m_{III}, p_{III}, m_{IV}, and p_{IV}:

$$m_{III} = \frac{\rho_2 A_1}{\rho_1 A_2} \qquad p_{III} = \frac{v_0 L_{2e}}{D_e}$$

$$m_{IV} = \sqrt{\frac{k_4 C_4}{k_3 C_3}}\,\frac{D_3}{v_0 L_3} \qquad p_{IV} = \frac{v_0 L_4}{\sqrt{D_3 D_4}}$$

in defining the equivalent diffusivity D_e by:

$$D_e = \sqrt{2\, D_m\, D_3} \qquad (m^2 s^{-1}) \qquad (25)$$

and in taking for v_0 the velocity calculated assuming that the layer of superstabilized conductors is bare (without layer insulation) and the current is confined to the composite:

$$v_0 = \sqrt{\frac{D_3 P_{j0}}{\Delta H_3}} \qquad (ms^{-1}) \qquad (26)$$

where P_{j0} is the average power density per unit volume dissipated by the elementary winding pattern without the layer insulation and assuming that the current is confined to the composite in the normal resistive state.

We thus establish, for all values m_{III}, p_{III}, m_{IV}, and p_{IV}, the existence of a propagation velocity for the normal zone v_V given by:

$$v_V = \frac{\nu_V}{\sqrt{1 + m_{IV}\dfrac{\tanh(p_{IV}\,\nu_V)}{\nu_V}}}\, v_0 \ (ms^{-1}) \qquad (27)$$

where ν_V is the super-stabilization and insulation corrective factor determined versus m_{III}, p_{III}, m_{IV}, and p_{IV}, by the implicit equation:

$$\tanh^2(p_{IV}\,\nu_V) + 3\frac{\tanh(p_{IV}\nu_V)}{p_{IV}\nu_V} + \left[\frac{2}{m_{IV}p_{IV}} - 1\right] = 2\,\frac{m_{III}p_{III}}{m_{IV}p_{IV}}\,\frac{1}{\nu_V\,[\tanh(p_{III}\nu_V) + m_{III}p_{III}\nu_V]} \qquad (28)$$

General method of calculating propagation velocity

After having presented the results of the studies of each of the four influences, it remains to explain how to integrate these individual studies in order to arrive at a general method of calculating propagation velocity. Let us proceed in progressive steps.

Case of a layer of multi-filament superconductive composites without layer insulation

In this case, only two influences must be taken into account: the current-sharing zone and the temperature-dependence of the physical characteristics.

We must remember that for the current-sharing zone:

$$v_I = \nu(m_I)\, v_0$$

where v_0 is the velocity calculated neglecting the current-sharing zone.

To consider the temperature-dependence of the physical characteristics, it seems logical to replace v_0 by the velocity calculated taking into account this influence. Thus we see that the velocity $v_{I\text{-}II}$ along a layer of composites without layer insulation is given by:

$$v_{I\text{-}II} = \nu_I(m_{II})\,\nu_2(m_2)\sqrt{\frac{D_t\, P_{jt}}{\Delta H_t}} \qquad (29)$$

Case of a layer of super-stabilized conductors without layer insulation

Now three influences must be taken into account: the current-sharing zone, the temperature-dependence of the physical characteristics, and the electromagnetic diffusion in the super-stabilizer.

We must remember that for the electromagnetic diffusion:

$$v_{III} = \nu_{III}(m_{III}, p_{III})\; v_0$$

where v_0 is the velocity calculated assuming that the current is confined to the composite.

To consider the influence of the current-sharing zone and the temperature-dependence of the physical characteristics, it seems logical to replace v_0 with the velocity calculated taking these influences into account. Thus we see that the velocity $v_{I\text{-}II\text{-}III}$ along the layer of calculations is given by

$$v_{I\text{-}II\text{-}III} = \nu_I(m_I)\,\nu_{II}(m_{II})\,\nu_{III}(m_{III}, p_{III})\sqrt{\frac{D_t\, P_{j0}}{\Delta H_t}} \qquad (30)$$

where m_I, m_{II}, and m_{III} are the parameters defined by Equations (4), (8), and (11), respectively, and p_{III} is the *second super-stabilization parameter* generalized in:

$$p_{III} = \nu_I(m_I)\,\nu_{II}(m_{II})\sqrt{\frac{P_{j0} L_{2e}^2}{2\, D_m \Delta H_t}} \qquad (31)$$

The other definitions remain the same.

To illustrate these results, we present, in Figure 6, the curve $v = f(I)$ calculated along a layer of bare ALEPH conductors (without layer insulation), and in Figure 7, the curves $v = f(I)$ for each of the influences.

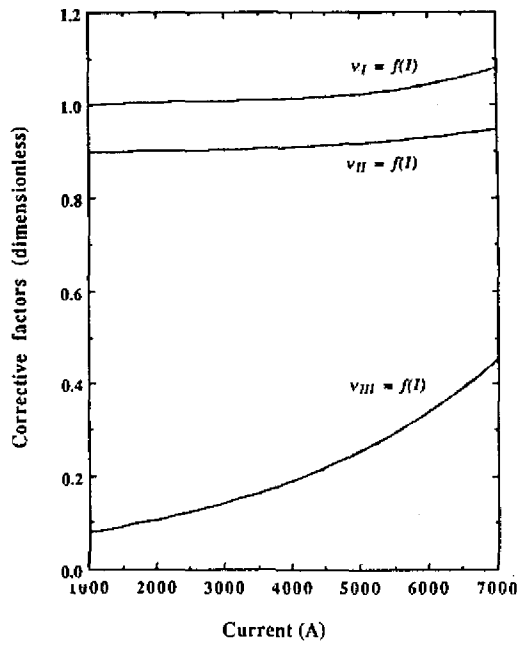

Figure 6. Propagation velocity along a bare layer of ALEPH conductors.

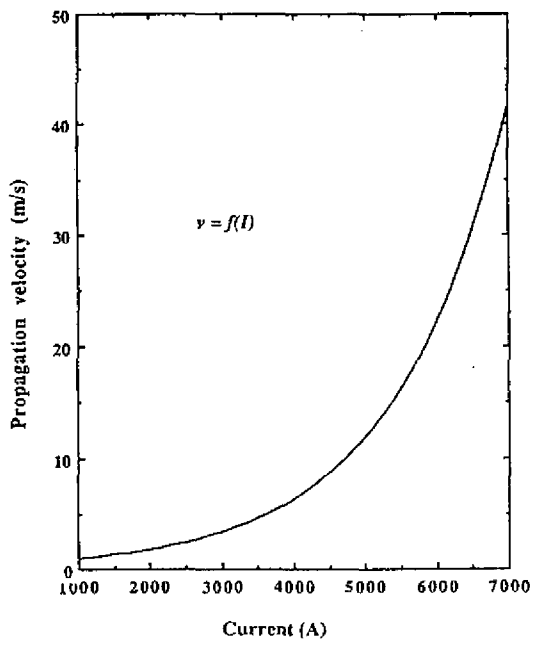

Figure 7. Comparison of the different influences.

Case of a layer of insulated conductors

Through reasoning similar to the above, we see that the propagation velocity along a layer of insulated composites is given by formula (23), and along a layer of insulated super-stabilized conductors by formula (27). by replacing v_0 with the velocity calculated taking into account the current-sharing zone and the temperature-dependence of the physical characteristics (v_0 is also to be replaced in the definitions of p_{III} and p_{IV}).

Conclusion

The previous equations allow us to consider all cases of indirectly-cooled windings, where the heat exchanges with helium are negligible at the scale of the propagation phenomenon. However, our modelization has a weakness. We see that all the interface resistances, either electrical (between the composite or the super-stabilizer) or thermal (between the layer of conductors and the layer of insulation) equals zero. It can occur that in certain configurations these become dominant.

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