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ASYMMETRY OF THERMAL PROPAGATION VELOCITY IN A LONG FORCE-COOLED SUPERCONDUCTING TEST LINE*

J. K. Hoffer, E. C. Kerr, and W. C. Overton, Jr.[†]

ABSTRACT

We have observed the phenomenon of thermal destruction of superconductivity by current in a force-cooled test model power transmission line of 20 m length at currents up to 9 kA and temperatures between 8 K and 14 K. This line, fabricated by soldering doubly-stabilized Nb₃Sn tapes to each side of a bar of Ofhc copper (0.3 cm x 1.58 cm), was enclosed in a German silver cryogen flow tube. The cryogen (He gas) was controlled at a flow rate of 0.5 to 0.7 gm/sec. Destruction was initiated by application of a short duration heating pulse to a small section of line. The velocity of N-S interface zone propagation was measured over 1.0 m test sections located downstream and upstream from the initial section. The upstream moving zone is always in a nearly-constant-temperature cryogenic environment. However, downstream portions contact an environment preheated by Joule heating in upstream normal N zones and thus transfer less heat and exhibit a much higher velocity. This qualitative explanation of the observed dramatic velocity asymmetry is to be supplemented by a more precise description of the physics of the moving N-S interface which must include a proper model for the heat conductance into the cryogen. Various models for heat conductance can be tested in velocity calculations.

I. INTRODUCTION

Current-carrying superconductors at a temperature $T < T_c$ exhibit the phenomenon of thermal propagation when a short section of conductor is caused to undergo the transition from the superconducting (S) state to the normal (N) state.¹⁻⁴ The Joule heating $\rho_n J^2$ (ρ_n —N-state resistivity, J —current density) causes expansion of the N-region in the vicinity of the section at which nucleation of the N-state began. When the current is large enough, the N-region continues expansion in two directions, at essentially constant velocity (at constant current) until the N-state prevails over the full length of conductor. One can measure this velocity of N-S interface zone propagation with high experimental accuracy.

This phenomenon, first observed in thin film superconductors deposited on a substrate,¹ has been further studied in thin films,^{2,3} wires,³⁻⁶ composite superconductors,^{7,8} and, in the present work, on a 20 m long test model of a possible conductor for a superconducting power transmission line (SPTL). A cross section of this particular test line is shown schematically in Fig. 1. We have performed velocity measurements on this line at currents up to 9 kA. Apparently, this is the highest current at which thermal propagation studies have been carried out to date.

Theoretical work, aimed toward a quantitative understanding of the phenomenon, has been hampered by the necessity of making various approximations for the low temperature realm. One of the most difficult problems is that of the heat transfer from the expanding N-region (which is undergoing Joule heating) and from the shrinking S-region into the immersing cryogen. Extant theories of Kapitza conductance, which are known to be only partially valid, have been applied to the case of heat transfer from the conductor into a stationary cryogen with some degree of success.⁹ However, in the present case of the flowing cryogen, the problem is much more

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difficult. A number of papers¹⁰⁻¹² on this subject show a relationship between the upstream velocity, the downstream velocity, and the cryogen flow velocity. Comparison with our present experimental velocity data indicates serious discrepancies in these theoretical relationships. The data and discussions of this paper should, hopefully, provide additional insight toward a better understanding of these complex phenomena.

We give in Sec. II the construction details of the composite superconductor, a description of the cryogenic test bed, and experimental aspects of the velocity measurement scheme. We discuss in Sec. III the velocity data and in Sec. IV we discuss these results in terms of extant theoretical models.

II. EXPERIMENTAL

The ribbon indicated in Fig. 1(a) was supplied by a commercial manufacturer. It was made by reacting a 50 μ m thick Nb strip precoated with a double layer of Sn. This resulted in a 14 μ m thick unreacted center between two 18 μ m layers of Nb₃Sn. This was then sandwiched between two 127 μ m stabilizing layers of copper ribbon held in place by Pb-Sn solder. The ribbons, as supplied, were then soldered to each side of the copper bar with In-Sn solder.

The resulting 20 m test line was then housed in a German silver cryogen flow tube and arranged in the test bed as indicated in Fig. 1(b). During assembly, carbon-in-glass thermometers were attached at points P₂-P₇ and voltage pickoff probes were soldered to the line at points P₂, P₃, P₄, P₅, P_{6A}, P_{6B}, P_{6C}, P_{6D}, and P₇.

The cryogen gas inflow was at P₂ and the outflow was at P₇. Power was fed via potheads cooled to L⁴He to the line near points P₂ and P₇. The power supply was made up of submarine batteries connected in series-parallel and was precisely controlled by a power trans-

Fig. 1. (a), Schematic of copper stabilized composite superconductor as described in text; (b), Arrangement of 20 m (overall length) conductor in test bed. Cryogen flow was always in the direction from P₂ to P₇. Electric current, supplied via L⁴He cooled potheads, could be connected with plus at P₂ or at P₇. Nominal mode was with plus at P₇. Heater winding was centered about P₆.

resistor pass bank composed of 120 heat sinks. Each water-cooled heat sink consisted of 12 power transistors (Motorola 2N4276) which was controlled in turn by a driver using a single 2N4276. Each heat sink could provide controlled current values up to 360 A. The overall system, when completed, will have the capability of supplying precisely controlled currents up to 42.2 kA. For the present experiments a sufficient number of heat sinks had been completed to permit controlled currents up to 14 kA.

The $L^4\text{He}$ supply for the cryogen flow control system was independent of that for potheads. One of us, ECK, designed a system that could provide controlled cryogen flow rates of ^4He gas, two-phase vapor and liquid, or liquid ^4He , that required only $L^4\text{He}$ from a supply dewar as the input cryogen. The line temperature at point P_6 of Fig. 1(b) could be set anywhere between 4 K (to an accuracy of 0.1 K) and 20 K (to an accuracy of about 0.3 K). The procedure was to allow the flow rate to stabilize while the temperature at point P_6 of Fig. 1 came to within about 0.2 K of the desired value.

The resistive heater of Fig. 1(b) was noninductively wound over a 45 cm length of the sample midway between the 60 cm section between voltage probes P_{6B} and P_{6C} . The heater was tapped at the 1/3 position allowing the heat pulse to be applied to lengths of 15, 30, or 45 cm. These design options proved useful in the acquisition of velocity data. After the application of a heat pulse, some 100 to 250 msec of time delay lapsed before Joule heating took over and initiated the thermal propagation process. The amount of this delay was, of course, a function of the line thermodynamic properties such as the specific heat and diffusivity, which depend explicitly on temperature, and the internal Joule heating, which depends explicitly on the flowing current. The delay depends to a lesser extent on the heat transfer to the flowing cryogen because the heater section was fairly well insulated from the cryogen.

Differential amplifiers used to acquire velocity data were connected as follows: Downstream amplifiers between P_{6C} and P_7 and between P_{6D} and P_7 ; upstream amplifiers between P_{6B} and P_5 and between P_{6A} and P_5 . Amplifier outputs were connected to an oscilloscope with quadruple trace display capability. The analysis of the photographs of these displays led to the arrival times of the upstream S-N interface at P_{6B} and later at P_{6A} and the downstream arrival times at P_{6C} and later at P_{6D} . Complete velocity determinations were possible only if all four arrival times could be determined. Unfortunately, this effort was sometimes thwarted when the protective circuits of the power supply control system caused shutoff of the power before the upstream propagation could reach probe P_{6A} .

We require knowledge of the function I_c versus T , where I_c is the critical current of the force-cooled line, in any subsequent theoretical analysis of the thermal propagation velocity. Theories of the critical current do not usually extend to such complicated geometrical configurations as we show in Fig. 1(a), nor do they take account of the heat transfer to the flowing cryogen in a reliable manner. Therefore, we have had to make an empirical determination of this function. We use the method whereby the temperature at point P_7 of Fig. 1(b) was set at a constant value at constant cryogen flow rate while the current was gradually increased. At I_c the jump to the N-state occurred and the N-S interface began propagating upstream, initially at a very high velocity which slowed somewhat because the upstream points were at a slightly lower temperature than T_7 at P_7 . This experiment defined the critical current indicated by the solid curve of Fig. 2, which is smoothed through the experimental points. Note that the critical current at 4.0 K is 12.5 kA, while i_0 is estimated to lie between 14 kA and 15 kA.

Fig. 2. Critical current of test model SP11, determined by method described in text. Solid circles and solid curve are experimental points and corresponding smoothed curve, respectively. Dashed curve is for similar unstabilized version of same line. Dot-dash curve is twice the critical current of a similar test line with only one Nb_3Sn tape soldered to a copper bar.

III. VELOCITY DATA

The voltage between a pair of probes, for example P_{6C} and P_7 of Fig. 1(b), was always zero until the arrival of the N-S interface at P_{6C} . At this time, there was a sudden break in an otherwise flat oscilloscope trace. The break is, of course, due to the development of an increasing IR drop between P_{6C} and the instantaneous position of the interface. All of the quadruple traces were initiated simultaneously by a trigger derived from the leading edge of the heating pulse. The upstream and downstream velocities could then be determined from the analysis of the arrival times of the four trace breaks as recorded on oscilloscope photographs.

The procedure consisted of aligning the photograph on the traveling table of a combination table and zoom microscope. A rotating eyepiece could be set on the slope of the trace break so that with proper adjustments of the table position, the arrival times of the trace breaks could be determined with an accuracy of 1% to 5%.

Upstream and downstream velocities were measured at currents between 3 kA and 9 kA and with initial line temperatures (at point P_6 of Fig. 1) of 8.1 K to 8.3 K, 9.1 K to 9.2 K, and 11.8 K to 12.0 K. These experimental results plotted in Fig. 3 have been fitted by smooth curves A_d to C_d as shown. Curves A_d , B_d , C_d show downstream velocities and curves A_u , B_u , C_u show upstream velocities at 8.2 ± 0.2 K, 9.1 ± 0.1 K, and 11.9 ± 0.2 K, respectively. Curves B_d and B_u are dashed to show the experimental spread of the data. The errors are due mainly to uncertainties in temperature and cryogen flow rate. The job of resetting and equilibrating the system at the desired temperature and flow rate was difficult, time consuming, and expensive, in terms of the cost of $L^4\text{He}$. We therefore had to be content with somewhat less precision in these quantities. Consequently, we have not been able to observe, within experimental error, the possibility of a velocity asymmetry effect with respect to the direction of electric current flow. Although such an effect has been observed in measurements on small diameter tantalum wires (the dirty Ta used was a Type II superconductor) in a uniform cryogenic environment ($L^4\text{He}$ bath), it is probable that such an effect does not exist in the composite superconductor of Fig. 1.

Fig. 3. Velocity versus current in test line of Fig. 1. Open circles, triangles, squares: carriers of current flow parallel to direction of N-S interface propagation. Solid circles, triangles, squares: current carrier flow opposite to velocity vector. Solid curves smoothed through experimental data. Dashed curves indicate band of uncertainty of data.

IV. ANALYSIS

The separate longitudinal heat balance equations for the N- and S-regions, first expressed in moving coordinates by Cherry and Gittelman,³ have been improved and extended (Ref. 9 LT-14 paper) to take account of possible temperature dependences of K_N , C_N , K_S , C_S (thermal conductivities and specific heats of the metal), the transverse heat conductance into the cryogen in the form $H(T_P - T_B)$, and the entropy change for the moving interface. In Fig. 1, however, the Nb₃Sn ribbons are so thin in comparison to the thickness d ($=0.318$ cm) of the copper bar, that we commit little error in letting K_N , C_N of the N-side of the moving interface have the same temperature dependence as K_S , C_S of the S-side.

As shown in a recent analysis,¹³ this simplification results in a very convenient expression for the thermal propagation velocity. For the temperature range of present interest (8 K to 12 K) and the particular copper used ($\rho_{273}/\rho_{20} \approx 273/20 \approx 90$), the thermal conductivity can be safely expressed in linear T form $K_N = K_S = BT$ ($B = 0.758$ W-cm⁻¹-K⁻²). However, the specific heat is definitely T^3 in form in the 8 K - 12 K range but we can safely approximate C_N , C_S by the form AT^2 , where T_0 is the transition temperature of the N-S interface (determined from Fig. 2) provided A is properly chosen for $T_0 = T_0(1)$.

For Kapitza conductance into a helium bath the exponent $p = 4$ in Khalatnikov theory but experimentally falls in the range $4 < p < 6$ below 2 K. For heat conductance into a gaseous cryogen at a temperature $T_0 \approx 20$ K, the linear form $h(T - T_B)$ is usually used in engineering calculations but formal theories indicate this to be a poor approximation when the difference $(T - T_B)$ is several degrees K. We compromise with an assumed form $H(T^2/T_0 - T_B^2/T_0)$, which allows an immediate solution of the N-region and S-region heat balance equations. For the N-region of the line of Fig. 1, we have

$$\begin{aligned} \partial/\partial z [K_N(T) \partial T/\partial z] + v C_N(T) \partial T/\partial z + \rho J^2 \\ - 2(H_W/d + H_d/w)(T^2/T_0 - T_B^2/T_0) = 0 \end{aligned} \quad (1)$$

where moving coordinate $z = x - vt$ is measured with respect to the instantaneous position of the moving N-S interface, ρ = copper bar resistivity, J = current density in copper, $T = T(z)$, $H_W = htc$ for Nb₃Sn side wall

of width w , $H_d = htc$ for copper bar of thickness d . We rewrite (1) in the form

$$B y'' + v A T_0^2 y' + \rho J^2 - 2H(y - T_B^2/2) = 0, \quad (2)$$

in which $y = T^2/2$, $H = 2(H_W/d + H_d/w)/T_0$. The solution for y , subject to the boundary condition at $-\infty$ and at zero, where $y = T_0^2/2$, is then exact. We express this result in the form

$$T_N^2 = (T_0^2 - T_B^2 - \rho J^2/H) e^{\alpha z} + T_B^2 + \rho J^2/H, \quad (3a)$$

$$\alpha = -v A T_0^2/2B + (1/2)(v^2 A^2 T_0^2/B^2 + 8H/B)^{1/2}, \quad (3b)$$

$$= -vC/2K + (1/2)(v^2 C^2/K^2 + 8HT_0/K)^{1/2}, \quad (3c)$$

where $C = C_N(T_0)$, $K = K_N(T_0)$. This is valid for $z < 0$ for the interface moving at velocity v in the $+z$ direction. The corresponding solution for the S-region is then

$$T_S^2 = (T_0^2 - T_B^2) e^{-\beta z} + T_B^2, \quad (4a)$$

$$\beta = +vC/2K + (1/2)(v^2 C^2/K^2 + 8HT_0/K)^{1/2}, \quad (4b)$$

which is valid for $z > 0$ for an interface moving in the $+z$ -direction. Notice that the results (3c), (4b) for T^2 are similar to those obtained 16 years ago for T by Cherry and Gittelman³ who had assumed constant values for C_N , K_N , C_S , K_S , and a linear $h(T - T_B)$.

The experimental voltage trace Δ breaks signaling the arrival of the N-S interface were slightly rounded for the line of Fig. 1, whereas the trace breaks in certain other experiments were very sharp. This indicates a finite length of the propagating N-S transition zone. This condition can be represented as we show schematically in Fig. 4, in which some Joule heating occurs within the zone itself. We represent this by $\xi \rho J^2$, where ξ is the average length of the interface and f is the fraction of ρJ^2 obtained by integrating over the pattern of streamlines. Since $f = 100$ percent at the N-side of the zone and $f = 0$ at the S-side edge, the actual f should fall somewhere in the vicinity of 0.5. The proper calculation of f and ξ is a complicated problem and is considered elsewhere. The longitudinal heat balance equation for the interface itself is therefore

$$\begin{aligned} -(K_N dT_N/dz)_{-\xi} + (K_S dT_S/dz)_0 + \xi f \rho J^2 \\ = +\xi C(dT/dt) - \xi H(T_0^2 - T_B^2), \end{aligned} \quad (5)$$

in which T_0 is assumed as the average temperature of the interface zone and $CdT/dt = -vCdT/dz$.

Using the solutions (3c), (4b), in (5), we thus obtain the velocity in the form

$$vC/K = [2HT_0/K(g-1)]^{1/2}(g-2) - (\xi/2)[2HT_0/K(g-1)]$$

$$\times g^2(1-f) + \text{negligible terms in } \xi^2, \text{ etc.} \quad (6a)$$

$$g = \rho J^2/H(T_0^2 - T_B^2). \quad (6b)$$

The reason for the simplicity of this result stems from the fact that C_N , K_N are the same functions of T , respectively, as C_S , K_S , since all are dominantly properties of the copper bar.

Thus, if H is known, we can solve for the interface velocity v . However, v happens to be the known experimental quantity for both upstream and downstream cases, as shown by the results of Fig. 3. Thus, we should be able to solve (6a), (6b) for $H = 2(H_W/d +$

Fig. 4. Schematic of propagating N-S interface zone for the line of Fig. 1. Thickness of superconducting ribbons are greatly exaggerated. The left N-N-S boundary is at $z = -\xi$ and the right N-S-S is at $z = 0$, to the right of which $\rho J^2 = 0$. Solutions (3a), (4a) are matched at $z = 0$ (T assumed $= T_c$).

$H_0/w/T_c \approx 2 H_0(w+d)/wdT_c$. An initial value of H can be obtained by using only the leading term of (6a), i.e., by setting $\xi = 0$. One can then make a correction to H if ξ is known. In the present paper, in which we assume $\xi = 0$, values of H_0 corresponding to the experimental velocities of Fig. 3 are shown in Table 1 for upstream propagation.

It is of interest to compare values of H_0 calculated using measured velocities and (6a)-(6b) with h calculated via the well known Dittus-Boelter expression. The appropriate expression to use is that for flow in the annulus between concentric tubes with heat transfer between the inner tube and the gas stream. In our case, we assume the cross sectional area of the inner tube is the same as that of the conductor of Fig. 1. We shall use the formula

$$h = 0.023 (k/d_e) \text{Re}^{0.8} \text{Pr}^{0.4} (T_c/T_B)^{-0.7} (d_2/d_1)^{0.45}$$

in which d_e = effective (hydraulic) diameter, $k = {}^4\text{He}$ gas thermal conductivity at T_B , Re = Reynolds number at T_B , Pr = Prandtl number at T_B , d_2 , d_1 are outer and inner diameters, respectively. Values of k , C_p , viscosity, and gas density needed to calculate Re and Pr are given in NBS Technical Note 631 (Nov., 1972). The flow Reynolds number was in the range 2×10^4 to 4×10^4 .

If we replace $\text{Re} = Gd/\mu$, where G = mass velocity ($\text{gm-cm}^{-2}\text{-s}^{-1}$), μ = viscosity, by $(G/\rho)(\rho d/\mu) = U(\rho d/\mu)$, where U = linear flow velocity, we can then let $U = u$ (actual linear flow velocity) or $U = v + u$ (gas velocity relative to upstream propagation velocity). We show in Table 1 the $h_1(u)$ or $h_2(v + u)$. Note the significant differences in these two h 's.

TABLE I
Calculated h 's H_0 , h_1 , and h_2

$I(\text{kA})$	$T_B(\text{K})$	$T_c(\text{K})$	v_{up} cm/s	H_0 W/(cm ² K)	h_1 W/(cm ² K)	h_2 W/(cm ² K)
5	8	12.9	15.5	0.0205	0.266	0.301
6	8	11.9	50.0	0.0331	0.281	0.397
7	8	10.8	88.7	0.0597	0.302	0.515
8	8	9.6	133.8	0.1352	0.328	0.670

The cryogen temperature T_B encountered by the N-S interface moving upstream is essentially the initial line temperature just before application of the heat pulse to the heater of Fig. 1. However, the T_B encountered by the downstream-moving interface is somewhat larger due to preheating by upstream portions. The linear velocity u will also be faster. But we can cal-

culate this T_B via (6), since the downstream velocity is known from the data of Fig. 3. See Table 2.

TABLE II.
Downstream cryogen temperatures $T_B^{(1)}$, $T_B^{(2)}$ calculated via (6) using h_1 of Table I and measured downstream velocity. The h_2 used for $T_B^{(2)}$ is arbitrarily chosen to be $1.2 H_0$.

$I(\text{kA})$	$T_B(\text{K})$	$T_c(\text{K})$	v_{down} cm/s	$T_B^{(1)}(\text{K})$	$T_B^{(2)}(\text{K})$
5	8	12.9	86.2	8.72	9.44
6	8	11.9	120.3	8.09	9.75
7	8	10.8	152.8	7.83**	8.35
8	8	9.6	190.2	7.88**	8.18

The T_B^{**} of Table 2 are, of course, not possible, but only a 20% increase in h_2 is needed to obtain $T_B^{(2)}$, which is suitably larger than T_B . Thus, the observed faster downstream velocities occur if there is only a slight increase in cryogen temperature. These results also show that steady-state classical heat transfer theory cannot be applied to the dynamical problem of thermal propagation. Recent theories¹⁰⁻¹² that show v_{down} to be a simple function of v and gas velocity u are also found to be incorrect since they use a fixed value of the h_2 .

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* h_2 denotes heat transfer coefficient.