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MEASUREMENTS OF TRAVELING TRANSITION ZONE ALONG A SUPERCONDUCTOR*

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The spatial variation of the temperature in a traveling superconducting-normal transition zone can provide valuable information on transient heat transfer in realistic coil conditions. In this paper, temperature wave curves are presented for several transport currents corresponding to propagation and recovery in a high magnetic field. The temperature profiles have been constructed in the form $T = T(x + vt)$ by measuring the wave velocity and the temperature at one point as a function of time. The temperature is measured directly with differential thermocouples; simultaneous voltage measurements provide a continuous temperature reference in the current sharing region. Information is given about thermocouple calibration in the high magnetic field and about the temperature and magnetic field dependence of the thermal conductivity of the sample.

I. INTRODUCTION

Measurements of the velocity of a normal region moving along a superconductor provide important information about the stability of that conductor — direct information about the full recovery current and the minimum propagating current, and indirect information about heat transfer to the helium bath. In a previous study¹ agreement between experiment and theory was not complete. To explain the discrepancies, transient heat transfer was introduced.^{2,3}

The present experiment represents an improvement over previous ones because the temperature in the moving normal zone was measured directly. With this additional information, the heat transfer can be determined at each point by using the heat balance, Eq. (1):

$$\frac{d}{dx} k \left(\frac{dT}{dx} \right) - vs \frac{dT}{dx} + (Q_J - \frac{QP}{A}) = 0 \quad (1)$$

where

- A = the cross sectional area of the conductor
- S = the specific heat of the conductor per unit volume
- Q_J = the Joule heating produced per unit volume of conductor
- Q = the heat flux per unit surface area from the conductor to the helium bath
- P = the cooled perimeter of the conductor
- k = the thermal conductivity of the conductor
- v = the velocity of the traveling wave
- S, k, Q, and Q_J (in the current sharing region) are all temperature dependent.

We measure the temperature at a fixed point on the conductor as a function of time and also measure the velocity of the moving transition zone. Then,

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From the fact that the traveling wave is of the form $T = T(x + vt)$, we deduce the instantaneous temperature distribution $T(x)$ along the conductor.

II. EXPERIMENTAL TECHNIQUE

Test Conductor Holder

A long sample of conductor is positioned in a transverse magnetic field using the holder shown in Fig. 1. The conductor is fixed in a helical groove

Figure 1

which is machined in the fiberglass cylinder. A nickel-chromium heater ribbon fills the bottom of a long section of the groove. It is insulated from the conductor by a thin tape. The test conductor is wound under tension over the heater to give good thermal contact. Voltage taps and thermocouples are soldered on the conductor. The space between turns is filled with epoxy in such a way that only one face of the conductor is exposed to helium; interturn heat flow is negligible. The axis of the sample holder and therefore the cooled face of the conductor are oriented vertically in the liquid helium bath.

Two short heaters are provided by bonding strain gages at the ends of the test section. Heating and measuring techniques are schematically described in Fig. 2. Propagation or recovery can be initiated from the top or from the bottom.

In propagation experiments, we pulse only one short heater. In recovery experiments, the heating sequence (Fig. 3) is more complex because we want to study recovery from a steady-state situation in which the conductor is normal and heated only by its transport current. It should be noted that inhibition of recovery by the two short heaters is a direct verification of the cold-end recovery process. It also provides a direct way to measure steady-state heat transfer.

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Figure 2

HEATING SEQUENCE FOR RECOVERY CASE

1. H_1 , H_2 , H_3 ARE TURNED ON.
THE CONDUCTOR BECOMES NORMAL OVER THE TOTAL LENGTH
2. LONG HEATER H_1 IS SWITCHED OFF.
THE CONDUCTOR ENDS START TO RECOVER. THE SECTION BETWEEN H_2 AND H_3 STAYS NORMAL AND ITS TEMPERATURE APPROACHES THE ASYMPTOTIC LIMIT
3. SHORT HEATER H_2 IS SWITCHED OFF.
THE NORMAL SECTION STARTS TO RECOVER FROM THAT END WHILE CURRENT IS STILL SUPPLIED TO H_3 UNTIL t_3

Figure 3

Thermocouple Calibration Versus Magnetic Field

For temperature measurement we used Au 0.07 at % Fe vs copper thermocouples with the reference junctions at liquid helium temperature. The following scheme was used for calibrating the magnetic field dependence of the thermocouples. The reference junctions were housed in a copper block epoxy potted in a stainless steel can (reference junction module, Fig. 2). A controlled heat pulse was applied to a heater tightly bonded to the copper block and induced a reproducible temperature excursion while the measurement junctions remained at bath temperature. We verified that the temperature history was not field dependent from the fact that the calibration ratio of thermopower at field to thermopower at zero field is the same for heating time constants as different as 50 msec and 1.25 sec. Temperature versus time is determined at zero field by using data found in the literature.^{6,7}

Test Conductor Thermal Conductivity. There are not many data in the literature on the magnetic field dependence of thermal conductivity.^{6,7} The heat conduction term is relatively large, especially in the steepest part of the temperature front. We

Figure 4

measured the thermal conductivity of our conductor at 0 and 7 T with the system described in Fig. 4, using the same type of thermocouples and calibration as for the front measurements.

III. RESULTS AND DISCUSSION

All velocity and temperature profile measurements were performed in a 7-T transverse magnetic field. Table I summarizes the main measured parameters of the test conductor.

Table I.

Outside dimension	$2.8 \times 1.9 \text{ mm}^2$
Cu/SC	$\frac{2.69}{1}$
Critical current at 7 T	851 A
RRR at zero field	200
$\frac{\rho(7T)}{\rho(0)}$	4.4
Thermal conductivity at 10 K	
at zero field	29 w/cm K
in a 7-T parallel field	17 w/cm K

The thermal conductivity at 0 and 7 T was extracted from the measurements under the assumptions that it varies directly with temperature in the range of 5 to 15 K and the contribution of the NbTi is negligible. We measured the conductivity in a parallel field. Fevrier et al.⁶ reported that the

effect of a parallel field is about 33% larger than the effect of a transverse field. We used that ratio to apply our parallel field thermal conductivity measurement to the wave front data. It should be noticed that at zero field the thermal conductivity of the sample has the same dependence on residual resistance ratio as the copper samples measured by L. Sparks' and Fevrier. The effect of a 7-T transverse field is to increase the Lorentz number by a factor of about two.

The 7-T thermocouple calibration curve in Fig. 5 was used to construct the temperature profiles in Fig. 6. In addition, voltage measurements between the two points where the thermocouples are located provided a direct measurement of the current sharing and critical temperatures.

Figure 5

Figure 6

Heat transfer to liquid helium is shown in Fig. 7 versus temperature difference. It was calculated only for temperatures above T_C . The heat capacity of

Figure 7

the holder and the epoxy potting were considered negligible.

Our data for transient heat transfer show much scattering due in part to such sources of uncertainty as differentiation of the measured temperature. However, we also observed a strong influence of convection in the bath on heat transfer. For example, turning on the short heaters too soon can prevent the conductor from going normal for a heat input to the long heater that otherwise would be high and long enough to quench the conductor. In other words, when a section of conductor is normal, cooling is improved due to the higher induced convection, not only near the normal section but also in the whole bath.

CONCLUSION

Most parameters involved in the stability of a superconductor are temperature and magnetic field dependent. The first step in the investigation of stability is the acquisition of basic data such as conductor temperature, thermal conductivity, and heat transfer.

Thermocouples represent a very convenient way for a direct measurement of instantaneous temperature even in high magnetic fields. Thermal conductivity measurements show that Lorentz number is not necessarily conserved at high field.

Heat transfer through a cooling interface can be strongly influenced by outside heat load. The study of transient heat transfer must be dissociated from external effects. It is especially suggested that in such experiments the effects of convection must be controlled.

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