Stability of Superconducting Wire With Various Surface Conditions in Pressurized He II (1)—Experimental Results

M. Ohya, S. Shigemasu, Y. Shirai, M. Shiotsu, and S. Imagawa

***Abstract*—Stability tests were performed for two small test coils wound with NbTi/Cu composite superconducting wires with different surface conditions respectively. One is a 0.5 mm-diameter bare wire with the copper ratio of 1.3. Another is the same wire with chemically oxidized copper surface. The stable limit current under constant magnetic field greatly increased by shifting to He II cooling from He I cooling for both wires, but stationary normal zones were observed in wide current area lower than the stable limit currents for the oxidized wire. The characteristic of the stability of a superconducting wire is more deeply dependent on the conductor surface condition cooled by He II than that in case of He I cooling.**

***Index Terms*—Cryogenic stability, Kapitza conductance, superconducting coils, superfluid helium.**

I. INTRODUCTION

SUPERFLUID liquid helium (He II) has excellent cooling properties such as highly effective thermal conductivity and stability for a local thermal disturbance on a winding of superconducting magnet. Therefore, He II is expected as a coolant for large-scale superconducting magnets for nuclear fusion facilities, accelerators and SMES.

Recently, we carried out stability tests of the Large Helical Device (LHD) conductor immersed in pressurized He I and He II [1], [2]. The LHD is a Heliotron-type fusion experimental facility for the research of fusion plasma near a reactor region [3]. The LHD conductor is a pool-cooled composite superconductor which consists of a NbTi/Cu Rutherford cable, a pure aluminum stabilizer, and a copper sheath with a chemically oxidized surface. As the results of the conductor tests, the maximum conductor current without a quench against a pulse heat input increased greatly by shifting to He II cooling from He I cooling. However, the increase in the stable limit current of the LHD conductor from saturated He I cooling to He II cooling was lower than that in a bare superconducting wire examined before [4]. Although some points are mentioned as the causes, such as a Cu-2%Ni layer with low thermal conductivity and a pure Aluminum stabilizer with long current diffusion time, the increase of Kapitza resistance by copper surface oxidization would likely affect the stability of the LHD conductor immersed in He II. Iwamato *et al.* measured Kapitza conductance of chemically oxidized copper surface in subcooled and saturated He II nearly at 1.8 K [5]. They reported that an oxidization surface has higher surface temperature than a polished surface at a certain heat flux because of both $R_{Cu-Oxidation}$ (interface resistance between the copper and the oxidation layer) and $R_{Oxidation}$ (thermal resistance of the oxidation layer). On the other hand, there has been little work on the influence of Kapitza conductance on stability of a superconducting coil immersed in He II.

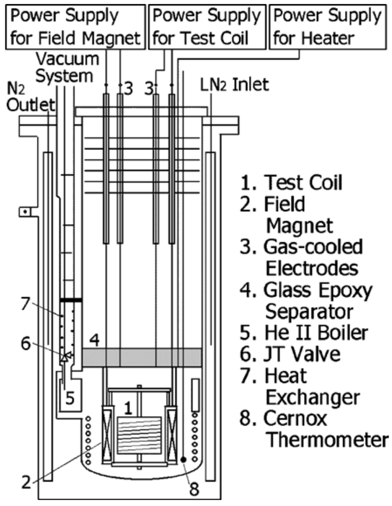

Fig. 1. Experimental apparatus.

The purpose of this study is to clarify the effect of Kapitza conductance on the stability of a superconducting coil immersed in He II.

II. EXPERIMENTAL APPARATUS AND METHOD

The experimental apparatus used in this work is shown schematically in Fig. 1. The Claudet-type cryostat is made of stainless steel. The inner bath of the cryostat is 45 cm in diameter and 157 cm in height with liquid helium contents of about 150 liters. There is a glass epoxy separator called λ-plate in the middle height of the inner bath. The He II compartment (He II bath with no free surface) has a volume of 74 liters. There is a superconducting magnet that impresses the magnetic field to the test coil in the He II bath, and the test coil is installed in it as shown in Fig. 1. The inner diameter and the outer diameter of the superconducting magnet is 20.3 cm and

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TABLE I
PROPERTIES OF TEST WIRES AND COILS

	Coil-1	Coil-2
Wire Diameter	0.5 mm	0.5 mm
Cu/NbTi	1.3	1.3
Insulation of Wire	Bare	Oxidized
Material of Bobbin	G-FRP	G-FRP
Coil Diameter	18 cm	18 cm
Coil Winding Height	10.2 cm	6.8 cm
Number of Turns	33	22

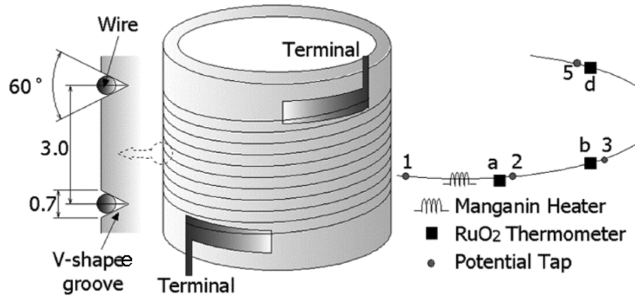

Fig. 2. Schematic illustration of test coil and test part (1 turn).

TABLE II
LENGTHS BETWEEN EACH TAPS

	Tap1-2	Tap2-3	Tap3-4	Tap4-5
Coil-I	20.0 mm	60.0 mm	60.0 mm	60.0 mm
Coil-II	60.0 mm	60.0 mm	60.0 mm	60.0 mm

Each thermometer is attached in 5 mm distance from nearest voltage tap.

29.2 cm respectively and 22.9 cm in height. It can generate a maximum of 7 T magnetic field at the center.

Stability tests were carried out with two superconducting coils wound with a bare wire on a G-FRP bobbin (Coil-I), and with a surface oxidized wire on a G-FRP bobbin (Coil-II). The first wire is a 0.50 mm-diameter NbTi/Cu composite bare wire with the copper ratio of 1.3. The second is the same wire with a chemically oxidized copper surface. Basic parameters of these coils are listed in Table I. The schematic illustration of the test coil is shown in Fig. 2. The superconducting wires are wound about 30 turns around each bobbin respectively. The wires were fixed in the grooves on the bobbins only with tension. For Coil-I, a manganin insulated wire is noninductively wound around the superconducting wire as a heater to induce a pulse-wise local thermal disturbance at the central part of the test coil winding. The heater surface is covered with a polyimide tape that has small thermal conductivity. For Coil-II, a manganin insulated heater is buried inside the bobbin in such a way that the cooling condition of the heater part is not disturbed by the heater. Voltage taps and $\mathrm{RuO_2}$ thermometers are attached on the positions shown in Fig. 2. The lengths between the taps are shown in Table II.

Experiments were performed according to the following procedure. 1) Set up the fixed magnetic field and the constant current to the test coil. 2) Give the pulsive heat input (20 ms width) by use of the heater to cause a bud of normal transition in the wire. 3) Measure the tap voltages and the temperature signals along the wire to know the behavior of the normal zone propagation. The tests were performed for the magnetic flux densities B from 1.1 T to 7.6 T and the bulk liquid helium temperatures T_b from 1.6 K to 4.2 K.

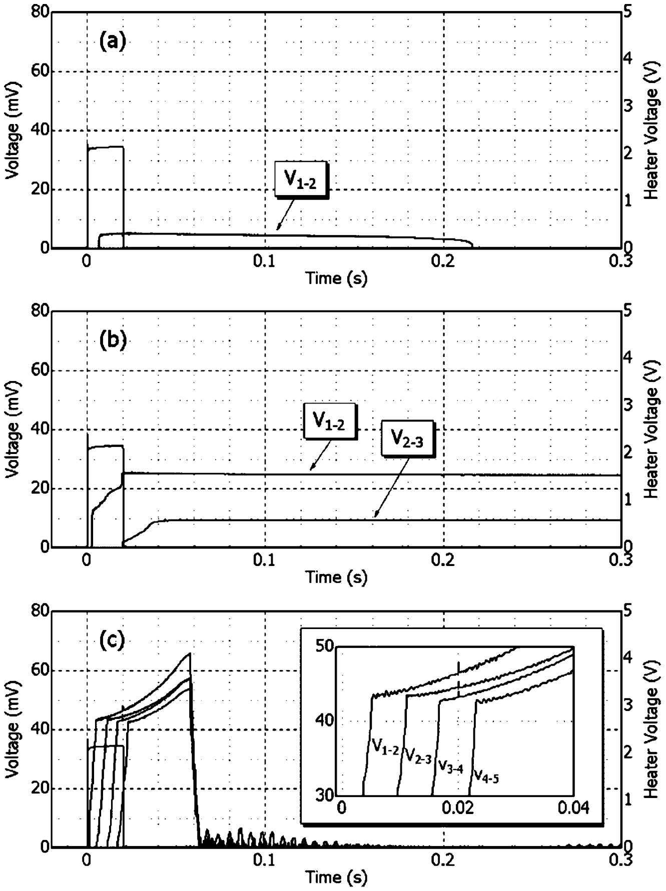

Fig. 3. Typical waveforms of the voltages between the taps for Coil-II belonging to three groups, respectively, for $T_b = 2.0$ K and $B = 7.2$ T. (a) $I = 70$ A, (b) $I = 130$ A, (c) $I = 152$ A.

III. RESULTS AND DISCUSSION

A. Stability Test Results for Coil-II

Characteristics of the normal zone propagation were classified into three groups depending on the magnetic flux density and the test coil current. Fig. 3 shows the typical waveforms of the voltages between the taps, for three groups respectively. These tests were performed for the liquid helium temperature of 2.0 K and the heat pulse of 68 mJ.

(Group I) As shown in Fig. 3(a), at $I = 70$ A, only tap voltage V_{1-2} arose as soon as the heat input was applied to the wire. Immediately after shutting off the heat input, the tap voltage began to decrease to zero and the normal zone started to shrink so that the wire recovered to the superconducting state.

(Group II) As shown in Fig. 3(b), at $I = 130$ A, tap voltages V_{1-2} and V_{2-3} arose in order, and did not returned to zero even after shutting off the heat input. However tap voltage V_{3-4} did not arise and terminal voltage of the whole test coil kept a certain value. One front of the normal zone stayed between Tap2–3 and the normal zone neither spread nor shrank, that is, a stationary normal zone was observed.

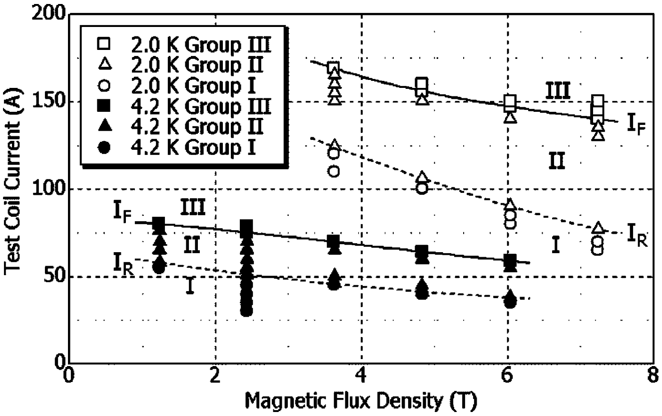

Fig. 4. Stability test results for Coil-II at $T_b = 4.2$ K and 2.0 K.

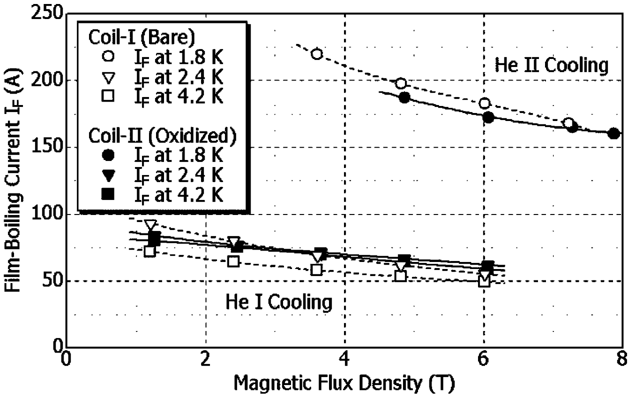

Fig. 5. I_F for Coil-I and Coil-II as a function of magnetic flux density for different liquid helium temperatures.

(Group III) As shown in Fig. 3(c), at $I = 152$ A, the tap voltages arose one after another. The normal zone was spreading through each of the taps, and the terminal voltage of the whole coil continued to increase until the quench protection circuit shut off the test coil current. Additionally, the tap voltages continued to rise up sharply for Group III. It means that the heat transfer on the wire surface shifted to the film boiling regime for Group III.

Fig. 4 shows the stability test results for Coil-II at the liquid helium temperature of 4.2 K and 2.0 K. The heat pulse was 68 mJ. We define the recovery current I_R as the largest current for which a normal zone will automatically disappear, and the film-boiling current I_F as the smallest current with which the heat transfer on the wire surface in normal state will shift to film boiling regime.

Fig. 5 shows the film boiling current I_F for Coil-I and Coil-II for different liquid helium temperatures. I_F for both coils at a certain magnetic field became slightly higher with the decrease of the liquid helium temperature from 4.2 K down to 2.4 K. It increases greatly by shifting to He II cooling from He I cooling. The difference between I_F of Coil-I and that of Coil-II was very small at 1.8 K since the critical heat flux (CHF) q_{cr} on a wire surface in He II hardly depends on the wire surface condition. However, as shown in Fig. 4, the current area of Group II at 2.0 K becomes much larger than that at 4.2 K for Coil-II. Even if a stationary normal zone occurs, the coil will not quench nor the wire burn out. However, the wire cannot recover to the superconducting state unless the transport current is lowered to less than the recovery current I_R. The stationary normal zones will deeply affect the stability of a superconducting coil immersed in He II. That is why, approaching the I_R line to the I_F line and making the Group II area as small as possible is important in order to make the effective use of the high q_{cr} of He II and improve the stability of a superconducting coil immersed in He II.

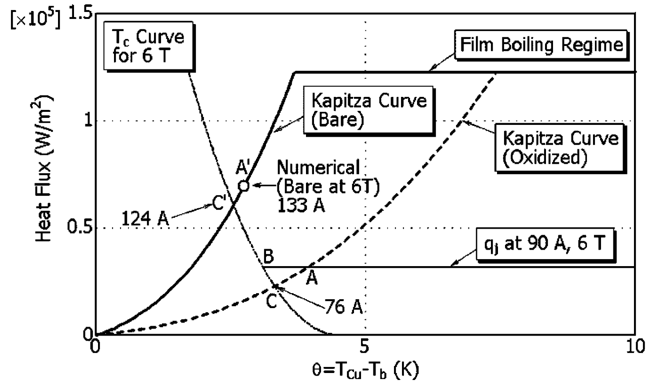

Fig. 6. Heat transfer curves for bare and oxidized surfaces at $T_b = 2.0$ K, and T_c curve for 6 T.

B. Effect of Kapitza Conductance on Stability

Now we discuss why the stationary normal zone occurs and what is necessary to raise the I_R line and reduce the Group II area. Heat transfer curves for $T_b = 2.0$ K are shown in Fig. 6. Vertical axis indicates the surface heat flux, and horizontal axis indicates θ that is the difference between the copper surface temperature T_{cu} and the bulk liquid helium temperature T_b. The solid line and the dashed line show the heat transfer curves in Kapitza conductance regime (nonboiling regime) for bare and oxidized copper surface, respectively, given by Iwamoto *et al.* [5]. These curves are expressed with the following equations.

$$q_c = 701.6\left(T_{Cu}^{3.001} - T_b^{3.001}\right)(Bare) \tag{1}$$

$$q_c = 202.5\left(T_{Cu}^{2.861} - T_b^{2.861}\right)(Oxidized) \tag{2}$$

Where q_c is the cooling heat flux. The critical heat flux q_{cr} on a wire surface in He II is hardly dependent on the wire surface condition, and q_{cr} for the wire used in this work at 2.0 K is calculated to be 1.23×10^5 W/m^2 by using the CHF correlation given by Shiotsu *et al.* [6]. In the film boiling regime, we regard the cooling heat flux as the constant value at $q_c = q_{cr}$.

At quasisteady state, one-dimensional equation of the heat conduction along the wire is:

$$\frac{d}{dx}\left(\frac{A}{P}k(\theta)\frac{d\theta}{dx}\right) = q_c - \frac{A}{P}Q_j = q_c - q_j \tag{3}$$

where A and P are the cross-sectional area and cooling perimeter of the wire, respectively, and k is its thermal conductivity. Since the groove on the bobbin is carved as shown in Fig. 2, P is set as 1.05 mm, which is 67% of the wire circumference. When the transport current of 90 A, which is I_R at 6 T for Coil-II (see Fig. 4), is supplied to the wire in the normal state, the Joule heat per unit volume Q_j is calculated to be

$1.71 \times 10^8\ \mathrm{W/m^3}$ by using magnetoresistivity of OFHC copper of $4.59 \times 10^{-10}\ \Omega\mathrm{m}$ (almost constant under 20 K) and Cu/NbTi ratio of 1.3. This Joule heat can be converted into the heat flux on the wire surface q_j of $3.19 \times 10^4\ \mathrm{W/m^2}$. In order that the wire recovers to the superconducting state, the wire temperature must be less than 5.09 K ($\theta = 5.09\ \mathrm{K} - 2.0\ \mathrm{K}$), which is the critical temperature T_c of the wire at 90 A. Thus, the recovery point at this transport current is determined as point B. The recovery curve (T_c curve) for 6 T is drawn as shown in Fig. 6 by similarly calculating for other current values. Next, the Joule heat line at 90 A and the Kapitza curve for the oxidized surface cross each other at point A (5.95 K). At this point, $d\theta/dx = 0$ holds by substituting $q_c = q_j$ in (3), that is, the temperature of point A indicates the central temperature of the normal zone. There will be a temperature distribution along the wire from the central temperature (point A) to liquid helium temperature T_c (point B). For the longitudinal temperature range from the central temperature down to T_c (point B), Joule heating will exceed the cooling because the former is almost constant and the latter decreases with decreasing temperature as shown in Fig. 6. On the contrary, cooling exceeds the Joule heating for temperatures lower than T_c because the latter is zero in the superconducting state. It is assumed that the stationary energy balance will be formed between the total excess heating and excess cooling energy through thermal conduction in the wire. A detailed numerical study on this assumption is performed in part 2 of this paper [7].

The stationary normal zone fundamentally results from the existence of point C in the nonboiling regime because of lower T_c of NbTi at higher magnetic field. The improvement of Kapitza resistance will be effective to raise the I_R line and reduce the Group II regime. For a bare wire, the point C rises up to point C′ (124 A) as shown in Fig. 6. I_R data for Coil-I was not obtained for this experiment since the heater part was covered with the polyimide tape. I_R obtained by numerical simulation is 133 A at 6 T [7], and this value is shown in Fig. 6 as point A′. The I_R for the bare wire will be about 1.5 times as high as that for the oxidized wire.

IV. CONCLUSION

The stability tests of the small test coils using two kinds of superconducting wires were performed for magnetic flux densities from 1.2 T to 7.2 T and the bulk liquid helium temperatures from 1.8 K to 4.2 K. Experimental results lead to the following conclusions.

The film-boiling current I_F for both coils at a certain magnetic field becomes slightly higher with the decrease of the liquid helium temperature from 4.2 K down to near the λ-temperature. It increases greatly by shifting to He II cooling from He I cooling, but the current area in which the stationary normal zone appears at 2.0 K is larger than that at 4.2 K for Coil-II (oxidized wire).

The stationary normal zone originates from lower T_c of NbTi at higher magnetic field, and the existence of the intersecting point of T_c curve and cooling curve in the nonboiling regime. It will be observed in the larger current area with larger Kapitza resistance.

Kapitza conductance deeply affects the stability of superconducting coil immersed in He II. It is necessary to use a conductor of small Kapitza resistance in order to make the effective use of high critical heat flux of He II.

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