Effect of Surface Oxidation on Stability of LHD Conductor Immersed in Pressurized He II

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

***Abstract*—Stability tests were performed on two small test coils wound with the Large Helical Device (LHD) conductors with different surface conditions. One used the conductor with a chemically oxidized copper surface, which is the same as that used for the LHD helical coils. Another used the same structural conductor with a polished copper surface. The stability tests were performed for the magnetic flux densities from 3 T to 7 T and at the bulk liquid helium temperatures from 2.0 K to 4.2 K at atmospheric pressure. Stability limit current for the LHD test coil was defined as a minimum dynamic propagation current, beyond which a short normal zone initiated by a thermal disturbance dynamically propagated to both sides along the conductor. There was a slight difference in the stability limit currents for the two test coils in case of He I cooling. However, the stability limit current for the polished coil was significantly improved as compared with that for the oxidized one in case of He II cooling. The Kapitza conductance on an oxidized copper surface is known to be quite smaller than that on a polished copper surface. One of the main factors that govern the stability of the LHD conductor cooled by He II is the Kapitza conductance.**

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

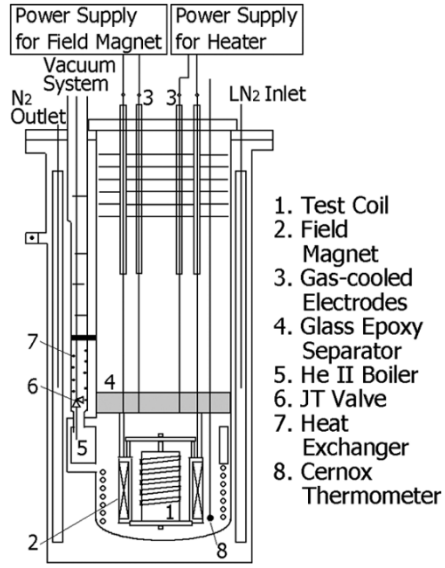

Fig. 1. Schematic diagram of the experimental setup.

I. INTRODUCTION

THE LARGE Helical Device (LHD) is a Heliotron-type fusion experimental device, which consists of a pair of superconducting helical coils and three pairs of superconducting poloidal coils. The helical coils with major radius of 3.9 m are pool-cooled with saturated liquid helium (4.4 K) in the present Phase I condition [1]. During the excitation tests of the LHD superconducting coil system, a normal transition occurred at the innermost layer of the helical coils, and a coil quench followed [2]. This event occurred at the current and the magnetic field slightly lower than the design operation point. In order to achieve a higher magnetic field, the change of the cooling mode to subcooled He I cooling is planned, and the liquid helium temperature would be lowered to 1.8 K in the Phase II program.

Previously, we carried out the stability tests of a small LHD conductor coil immersed in pressurized He I and He II [3], [4], and the advantage of He II cooling in the stability of the LHD conductor was clarified in comparison with He I cooling. However, the dynamic one-side propagation of the normal zone was observed in a wide current range below the quench current with lowering the liquid helium temperature. The dynamic one-side propagation phenomenon is the one in which a short normal zone initiated by a thermal disturbance propagates to only one side along the conductor and disappears in a lower magnetic field area. This phenomenon may lower the stability limit of the LHD helical coils when the higher excitation of the LHD magnet is realized by lowering the liquid He temperature.

The surface of the LHD conductor is chemically oxidized, and the Kapitza conductance on an oxidized copper surface is known to be quite smaller than that on a polished copper surface [5], [6]. In preceding papers, we described the stability tests for the thin superconducting wire coils with different surface conditions and the results showed that the maximum recovery current of the coil decreased with decreasing the Kapitza conductance on the wire surface [7], [8]. The Kapitza conductance will also affect the stability of the LHD conductor immersed in He II.

In this paper, the effect of the Kapitza conductance on the stability of the LHD conductor cooled by He II was studied experimentally in two small test coils wound with the LHD conductors with different surfaces.

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

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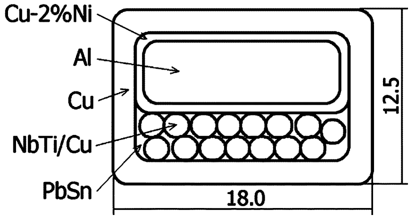

Fig. 2. Cross-sectional view of the LHD conductor.

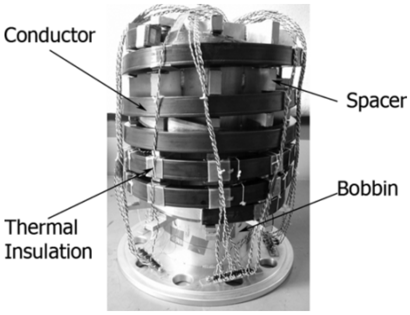

Fig. 3. Photograph of the LHD test coil (Coil-I).

TABLE I
PROPERTIES OF TEST COILS

	Coil-I	Coil-II
Conductor Length	4746 mm	4746 mm
Conductor Surface	Oxidized	Polished
Coil Radius	84.3 mm	84.3 mm
Coil Winding Height	165.5 mm	165.5 mm
Turn Number	8	8
Joint Length	550 mm (1 Turn)	550 mm (1 Turn)
Inductance	7.6 μH	7.6 μH
Thickness of Insulation	1.0 mm	1.0 mm
Interval of Insulation	55 mm	55 mm
Rate of Exposure	67 %	67 %
Heater Resistance	11.50 Ω (at 4.2 K)	9.45 Ω (at 4.2 K)

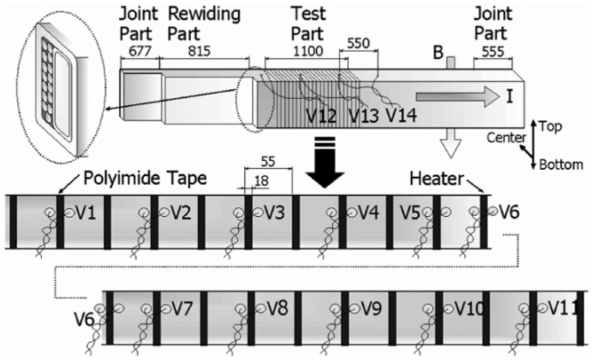

Fig. 4. Expanding diagram of the test conductor to the longitudinal direction.

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 has a volume of 74 liters. There is a superconducting magnet that impresses a magnetic field to the test coil in the He II bath. The inner diameter and the outer diameter of the superconducting magnet are 20.3 cm and 29.2 cm respectively and the height is 22.9 cm. It can generate a maximum of 7 T magnetic field in the center.

The LHD conductor consists of a NbTi/Cu Rutherford cable, a pure aluminum stabilizer and a copper sheath with electron beam welds. The cross-sectional view of the LHD conductor is shown in Fig. 2. Since it was not so easy to supply the transport current of dozens of kA to the test conductor through the λ-plate with a small heat leak, a transformer type current supplying method was used [3]. A small test coil was wound with a LHD conductor on a stainless steel bobbin and then short-circuited. The test coil was set coaxially in the center of the field magnet as shown in Fig. 1. A large current was induced in the test coil by increasing the current of the field magnet. Details of the current supplying method are given in [3].

Stability tests were carried out with two coils wound with an oxidized LHD conductor (Coil-I), which is the same conductor as that used for the LHD helical coil, and with a polished conductor (Coil-II). The photograph of the test coil is shown in Fig. 3, and the basic parameters of the test coil are listed in Table I. Fig. 4 shows the expanding diagram of the test conductor to the longitudinal direction. The enlarged view of the test part (1100 mm) and the layout of voltage taps are also shown in the same figure. An insulated nichrome heater was fixed on the conductor surface by the side of the bobbin in the center of the test part (see Fig. 4). The heater section with the length of 18 mm was covered with a polyimide tape with the thickness of 1.0 mm. For the test part, each contact section with the bobbin was similarly insulated with the polyimide tape and the rate of the exposure was set up to 67% for simulating the actual LHD helical coils.

Experiments were performed according to the following procedure. 1) Set up the fixed external magnetic field and the constant current to the test coil. 2) Give a pulse heat input by use of the heater to cause a bud of normal transition in the conductor. 3) Measure the tap voltages along the conductor to know the behavior of the normal zone propagation. The tests were performed at liquid He temperatures T_b from 2.0 K to 4.2 K and for the magnetic flux densities B from 3.0 T to 7.0 T at atmospheric pressure. Here, B indicates the magnetic flux density at the heater section taking into account the self-magnetic field of the test coil. The external magnetic field was applied on the conductor vertically downward and the test coil current flowed from the bottom to the top (in direction of V1 to V11 in Fig. 4).

III. RESULTS AND DISCUSSION

A. Typical Waveforms

Characteristics of the normal zone propagation were classified into the following three groups depending on the magnetic flux density and the test coil current. Fig. 5 shows the typical waveforms of the voltages between the taps for Coil-II (polished). These tests were performed at the liquid helium temperature of 2.0 K and for the input heat power of 170 W (100 ms).

(Group I) The normal zone was initiated only around the heater and the tap voltage of V6 arose in response to the heat input. In some cases, the V7 arose in a moment after the arising of the V6. After shutting off the heat input, the V6 began to

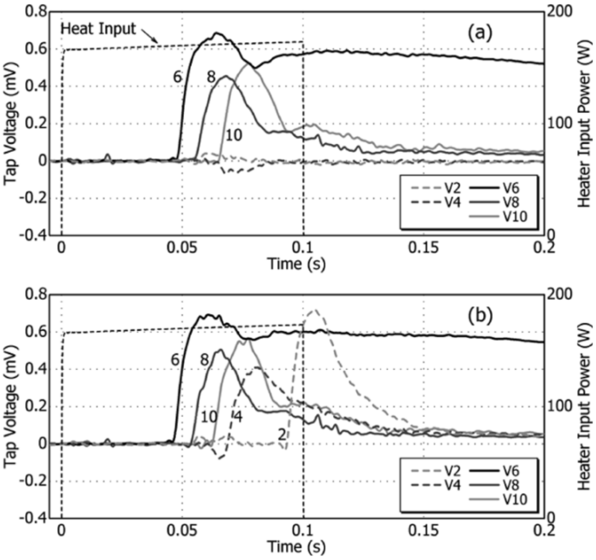

Fig. 5. Typical tap voltages between the taps for Coil-II at $T_b = 2.0\ \mathrm{K}$. (a) $B = 6.31\ \mathrm{T}, I = 23.37\ \mathrm{kA}$. (b) $B = 6.35\ \mathrm{T}, I = 23.84\ \mathrm{kA}$.

decrease to zero and the conductor recovered to the superconducting state.

(Group II) As shown in Fig. 5(a), at $B = 6.31$ T, $I = 23.37$ kA, the tap voltages of V6, V8 and V10 arose in order. The initiated normal zone propagated to only one side along the conductor, and a normal zone with a finite size separated from that of the heater section (V6). This normal zone is called "traveling normal zone". The traveling normal zone propagated through the test part, and disappeared in the upper part of the coil where the magnetic field was lower than in the test part. Finally the conductor recovered to the superconducting state. This phenomenon is called "dynamic one-side propagation phenomenon".

(Group III) As shown in Fig. 5(b), at $B = 6.35$ T, $I = 23.84$ kA, not only the tap voltages of V6, 8, 10 but the V2, 4 arose one after another. The initiated normal zone propagated to both sides along the conductor. Two traveling normal zones, which were separated from the both ends of the initiated normal zone respectively, propagated even in the rewinding part and caused the large decrease of the test coil current.

B. Stability of Coil-I

Fig. 6 shows the stability test results for Coil-I (oxidized) at the liquid helium temperatures of 4.2 K, 2.2 K and 2.0 K. The triangular, circular and square dots indicate the test results belonging to the three groups respectively. For all tests, input heat power was 132 W (50 ms).

Now the first minimum propagation current I_{p1} (dashed line) is defined as the current above which a normal zone will propagate to only one side along the conductor, and the second minimum propagation current I_{p2} (solid line) is defined as the current above which a normal zone will propagate to both sides along the conductor.

I_{p2} for Coil-I at a certain magnetic field became slightly higher with the decrease of the liquid helium temperature from 4.2 K down to 2.2 K, and it increased greatly by shifting to

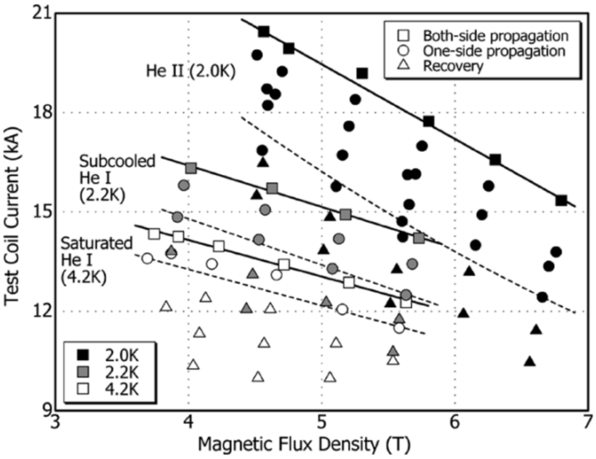

Fig. 6. Stability test results for Coil-I at $T_b = 4.2\ \mathrm{K}$, 2.2 K and 2.0 K.

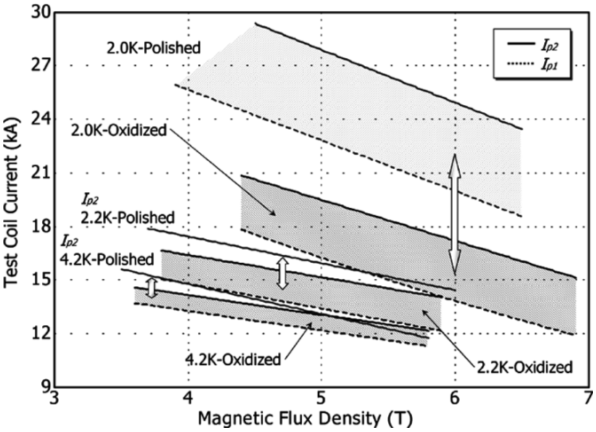

Fig. 7. Comparison of the stability test results for coil-I with those for coil-II.

He II cooling from He I. However, as shown in Fig. 6, the current range of Group II became wide with decreasing the liquid helium temperature. Even if dynamic one-side propagations occur, traveling normal zones will disappear in a lower magnetic field area and the coil will not quench. However, this phenomenon may lower the stability limit current of the LHD helical coils if the stable control of plasma is taken into consideration.

C. Effect of Kapitza Conductance on Stability

Fig. 7 shows the comparison between Coil-I (oxidized) stability and Coil-II (polished) one. The dashed and solid lines indicate I_{p1} and I_{p2}, that is, the dynamic one-side propagation phenomenon was observed in the shaded area. Each input heat power was 132 W (50 ms) for Coil-I, 141 W (100 ms) for Coil-II in He I and 170 W (100 ms) for that in He II.

In case of He I cooling (4.2 K and 2.2 K), there was a slight difference between I_{p2} for Coil-I and that for Coil-II. Noteworthy is that there was no shaded area for Coil-II, that is, the dynamic one-side propagation phenomenon was not seen for Coil-II. The polished conductor coil (Coil-II) was more stable than the oxidized conductor coil (Coil-I) although the critical heat flux q_{cr} on a polished copper surface in He I is slightly lower than that on an oxidized copper surface [9]. This may be because the temperature drop in the oxidized copper layer affected the transient stability of the oxidized conductor.

In case of He II cooling, as shown in Fig. 7, both I_{p1} and I_{p2} for Coil-II (polished) were significantly improved as compared with those for Coil-I (oxidized). For instance at the magnetic flux density of 5 T, I_{p1} for Coil-II was 1.5 times that for Coil-I, and I_{p2} for Coil-II was 1.4 times that for Coil-I. This is due to the increase of Kapitza conductance since q_{cr} on a conductor surface hardly depends on its surface condition in case of He II cooling [9]. The heat flux equations in the Kapitza regime for the oxidized and polished copper surfaces are expressed as the following ones [5].

$$q = 202.5\left(T_{Cu}^{2.861} - T_b^{2.861}\right) \cdots \text{Oxidized} \tag{1}$$
$$q = 701.6\left(T_{Cu}^{3.001} - T_b^{3.001}\right) \cdots \text{Bare} \tag{2}$$

Where q is the cooling heat flux in $\mathrm{W/m^2}$, T_{Cu} is the conductor (copper) surface temperature and T_b is the bulk liquid helium temperature in Kelvin. The critical temperature of NbTi is 6.92 K at the magnetic flux density of 5 T. Substituting $T_{Cu} = 6.92\ \mathrm{K}$ and $T_b = 2.0\ \mathrm{K}$ into (1) and (2), one obtains the heat flux of $4.97 \times 10^4\ \mathrm{W/m^2}$ for the oxidized surface and that of $2.27 \times 10^5\ \mathrm{W/m^2}$ for the polished surface. The cooling heat flux on the polished surface is 4.6 times that on the oxidized surface at the conductor surface temperature of 6.92 K. Such a higher heat flux on the polished surface in the Kapitza conductance regime makes Coil-II considerably more stable than Coil-I. The Kapitza conductance deeply affects the stability of the LHD conductor, and higher Kapitza conductance of the LHD conductor surface produces higher stability of the conductor in He II.

IV. CONCLUSION

The stability tests were performed on the small test coils wound with the LHD conductors with oxidized and polished surface respectively. The tests were performed for the magnetic flux densities from 3.0 T to 7.0 T and at the bulk liquid helium temperatures from 2.0 K to 4.2 K. Experimental results lead to the following conclusions.

For both coils, the minimum both-sides propagation current I_{p2} 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, but the current range, in which the dynamic one-side propagation phenomenon appears, expands with decreasing liquid helium temperature.

In case of He I cooling, there is a slight difference between I_{p2} for the oxidized conductor coil and that for the polished conductor coil. However the dynamic one-side propagation phenomenon is not seen for the polished conductor coil.

In case of He II cooling, the stability of the polished conductor coil is significantly improved as compared with that of the oxidized conductor coil. Kapitza conductance deeply affects the stability of LHD conductor immersed in He II, and higher Kapitza conductance on the LHD conductor surface produces higher stability of the conductor.

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