Cooling Stability Test of He II Cooled LHD Conductor (2)—Experimental Results

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

***Abstract*—Cooling stability tests of the Large Helical Device (LHD) conductor immersed in pressurized He I and He II were carried out. A small test coil wound and short-circuited with a LHD conductor on a stainless steel bobbin was used. The test coil was set coaxially in the center of a superconducting magnet (field magnet), which supplies a certain magnetic field to the test conductor. A large current was supplied to the test coil conductor by use of a transformer effect, that is, the test coil current was induced by increasing the current of the field magnet. Stability tests of the LHD conductor at a certain pulse heat input were performed for the magnetic flux densities from 1.2 T to 6.8 T and the bulk liquid He temperatures from 2.0 K to 4.2 K at atmospheric pressure. Experimental results can be classified into three groups. The normal zone arose only around the heater and disappeared after the heat pulse (Group I). The normal zone moved to only one side direction and disappeared (Group II). The normal zone spread on both sides and the conductor current decreased greatly (Group III). The maximum conductor current without a quench at the pulse heat input increased greatly by shifting to He II regime from He I regime. The advances of the He II cooling on the stability of the LHD conductor were confirmed.**

***Index Terms*—Aluminum stabilized superconductor, cryogenic stability, superfluid helium.**

I. INTRODUCTION

THE Large Helical Device (LHD) is a Heliotron-type fusion experimental facility for the research on a fusion plasma [1]. Two helical coils with the major radius of 3.9 m are pool-cooled with 4.4 K liquid helium in the present research stage [2]. During the recent experimental cycles of the LHD, excitation tests of the superconducting coil system have been carried out and the normal transition events have been observed in the helical coils [3]. These events occurred at the current and the magnetic field slightly lower than the specified operation point (current 13 kA, magnetic flux density 7 T, temperature 4.4 K).

A composite superconductor, which is used for the helical coils, consists of a NbTi/Cu Rutherford cable, a pure aluminum stabilizer and a copper sheath with electron beam welds. The conductor has rectangular shape with 12.5 mm × 18.0 mm size, and Cu-oxide layer covers the outer surface of it [4]. The cross-sectional view of the LHD conductor is shown in Fig. 1. The transient stability test of a large-scale superconductor stabilized with a pure aluminum, whose electric resistivity was much lower than that of copper, was performed [5]. It was indicated that the current diffusion time of the pure aluminum is so large that the transient longitudinal resistance of the stabilizer remains much higher than that in the steady state. Such a phenomenon might affect the stability of the conductor.

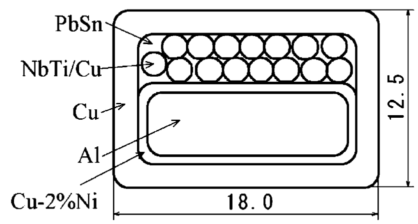

Fig. 1. Cross-sectional view of the LHD conductor.

In this paper, the cooling stability test results of the test coil using the LHD conductor immersed in subcooled He I and He II at atmospheric pressure are described. There are few experimental data obtained by the stability tests for such a pool-cooled conductor with the critical current of dozens of kA in He II. This result will serve as valuable data in case when discussing the improvement in the cooling stability of the LHD helical coils by shifting to He II cooling.

II. EXPERIMENTAL SETUP

A. Cryostat and Field Magnet

A schematic of the experimental setup is shown in Fig. 2. The Claudet-type cryostat made of stainless steel was used. The inner bath of the cryostat is 45 cm in diameter and 157 cm in height with the 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 (field magnet) that impresses a magnetic field to the test coil in the He II bath. It can generate a maximum of 7 T magnetic field at the center of it. The specifications of the field magnet are given in Table I.

B. Current Supply Method

Since the critical current of the LHD conductor is dozens of kA, it is not so easy to supply such a large current to the test conductor through the λ-plate with small heat link. To solve this problem, a transformer type current supplying method was used. A small test coil was wound with a LHD conductor on a stainless steel bobbin and short-circuited to make a superconducting loop. The test coil was set coaxially in the center of the

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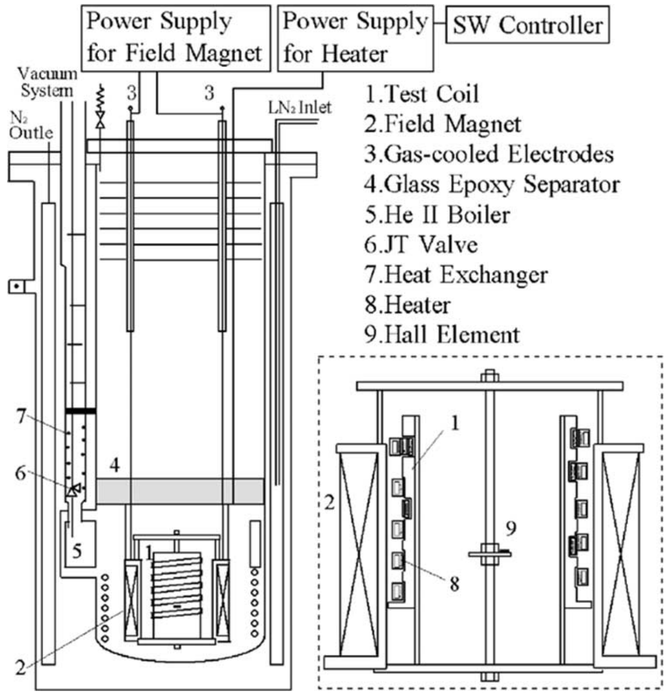

Fig. 2. Schematic of the experimental setup.

TABLE I
SPECIFICATIONS OF THE FIELD MAGNET AND THE TEST COIL

Field Magnet	
Inner Diameter	203 mm
Outer Diameter	292 mm
Overall Length	229 mm
Inductance	31.4 H
Specified Current	133 A (at T_b = 1.8 K)
Field to Current Ratio	0.053 T/A (at center of the magnet)
Test Conductor	
Cross Section	12.5 mm × 18.0 mm
Critical Current	22.0 kA (at B = 7 T, T_b = 4.4 K)
Specified Current	13.0 kA (at B = 7 T, T_b = 4.4 K)
Conductor Length	4200 mm
Test Coil	
Coil Radius	84.3 mm
Coil Winding Height	160 mm
Turn Number	7
Inductance	6.04 µH
Joint Length	503 mm
Test Part	
Thickness of Insulation	1.0 mm
Interval of Insulation	55 mm
Rate of Exposure	67%
Heater Resistance	13.9 Ω (at 2.0 K)

field magnet as shown in Fig. 2. Since the test coil and the field magnet were inductively coupled, a large current will be induced in the test coil by increasing the current of the field magnet. The calculated ideal current transfer ratio is about 1263. To obtain a certain set of the test coil current and the external magnetic field, only the test coil current was damped at an appropriate time by generating a normal zone in the conductor by use of a heater. Details of the current supplying method are given in [7].

C. Test Coil and Conductor

The photograph of the test coil is shown in Fig. 3, and the expanding diagram of the test conductor to the longitudinal

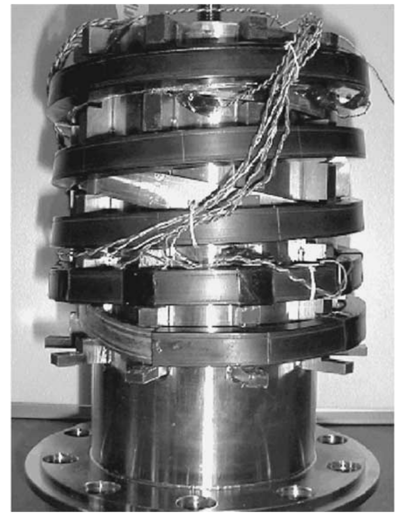

Fig. 3. Photograph of the LHD test coil.

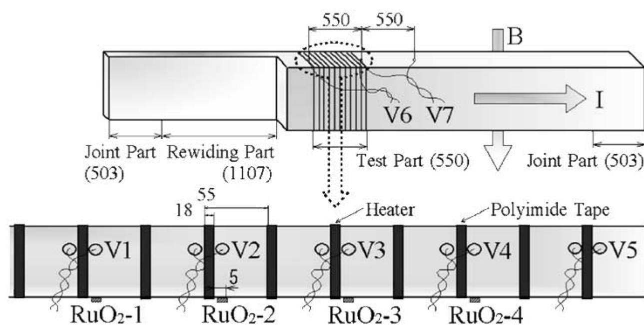

Fig. 4. Expanding diagram of the test conductor to the longitudinal direction.

direction is shown in Fig. 4. The enlarged view of the test part (550 mm: 1 turns) and the layout of the voltage taps and the thermometers of RuO_2 are also shown in the same figure. The total length of the conductor is 4200 mm. The aluminum stabilizer was cut off by 1107 mm from one end of the conductor. Firstly, the conductor of this part was wound 2 turns from the bottom of the bobbin to the top as a rewinding part. The conductor including the test part was wound 5 turns from the bottom to the top over the rewinding part. Then the conductor was soldered with the rewinding part at the top of the coil with the length of 503 mm to make the short-circuited coil with the significantly small resistance. The resistance of the short-circuited coil was measured to be about 0.45×10^{-9} Ω. The test coil current was calculated from the magnetic flux density measured by a Hall element located at the center of the test coil as shown in Fig. 2. Details of measuring the test coil current are given also in [7]. A resistive nichrome heater, which was insulated by a polyimide tape with the thickness of 50 μm, was mounted between the spacer and the conductor at the central part of the test part. 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, the contact sections with each stainless spacer were similarly insulated with the polyimide tapes and the rate of exposure was set up to 67%. The specifications of the test coil are given in Table I.

D. Experimental Procedure

Experiments were performed according to the following procedure:

1) Set the test conductor current and the external magnetic field;
2) Give the pulsive heat input by use of the heater located at the center of the test part to cause a bud of normal transition in the conductor. The input heater power W was 125 W, and the heater pulse width Δt was 100 ms or 200 ms;
3) Measure the tap voltages and the temperature signals along the conductor to know the behavior of the normal zone propagation. The tests were performed for the bulk liquid He temperatures Tb from 2.0 K to 4.2 K and the magnetic flux densities B from 1.2 T to 6.8 T at atmospheric pressure. Where, B indicates the magnetic flux density of the heater section considering 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 as shown in Fig. 4.

III. Experimental Results

A. Typical Waveforms of Stability Test Results

Characteristics of the normal zone propagation were classified into three groups depending on the magnetic flux density and the test coil current. Fig. 5 shows the typical waveforms of the voltages between each taps and the test coil current, for three groups respectively. These tests were performed for the liquid He temperature of 2.0 K and the heater pulse width of 200 ms.

(Group I) The normal zone arose only around the heater and only the tap voltage V3 including the heater section was appeared. The normal zone disappeared after shutting off the heat input as shown in Fig. 5(a).

(Group II) As shown in Fig. 5(b), the tap voltage V3 appeared at first due to the heater input. About 20 ms later, only the tap voltage V5 appeared. The voltage V5 disappeared after a while. The voltage V6 between turns including the heater section appeared for a certain period, and the voltage V7 between turns upper side of the test part followed. This result shows that the initiated normal zone at the heater part propagated only upper side of the test coil. Then the normal zone with a finite size was separated from that of the heater section and traveled along the conductor. It is expected that there is some time delay between the appearance of the normal zone and the current diffusion to the aluminum stabilizer at a certain point of the conductor. Therefore, the current shifted to the stabilizer from the tail end of the normal zone, where the conductor recovered to the superconducting state. This phenomenon is called “traveling normal zone” [4]. The traveling normal zone moved through the taps V4 and V5, and disappeared in the upper part of the test coil where the magnetic field was lower than that of the test part. Finally, the test coil recovered to the superconducting state, and the test coil current hardly decreased.

(Group III) After the appearance of the tap voltage V3, both V1 and V5 appeared as shown in Fig. 5(c). Although the tap voltages of the test part except the heater section (V3) recovered to the superconducting state within a short time, V6 and V7 between each turns still had negative value. This result shows that traveling normal zones, which were separated from both ends of the initiated normal zone, propagated for both sides through the voltage tap V1 and V5 respectively. Then the normal zone spread and stayed even in the rewinding part that has no aluminum stabilizer, and it caused the large decrease of the test coil current.

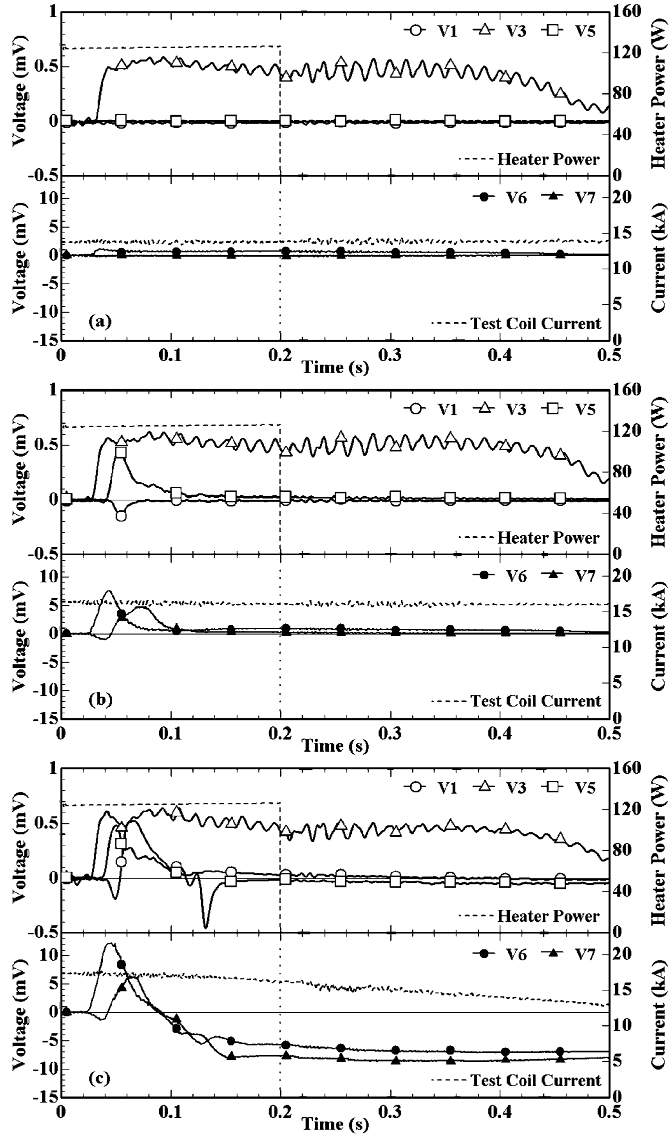

Fig. 5. Typical waveforms of the voltages between each taps and the test coil current for the liquid He temperature of 2.0 K. (a) $B = 6.35$ T, $I = 13.8$ kA, (b) $B = 6.48$ T, $I = 16.3$ kA, (c) $B = 6.57$ T, $I = 17.4$ kA.

Fig. 6 shows one of the overall trends in the test results belonging to Group III. The test coil current decreased with the propagation of the normal zone, and the field magnet current also decreased slightly. However, as shown in Fig. 5, the classification of the test results into the three groups was determined at very early time of about 30 ms from the normal generation in the heater section. The attenuation ratio of the test coil current was about 2% at the time, and the decrease of the field magnet current was not observed yet. The attenuation of both currents caused by the current supplying method hardly affects the classification. The stability examination of the LHD conductor will be carried out by use of the proposed method.

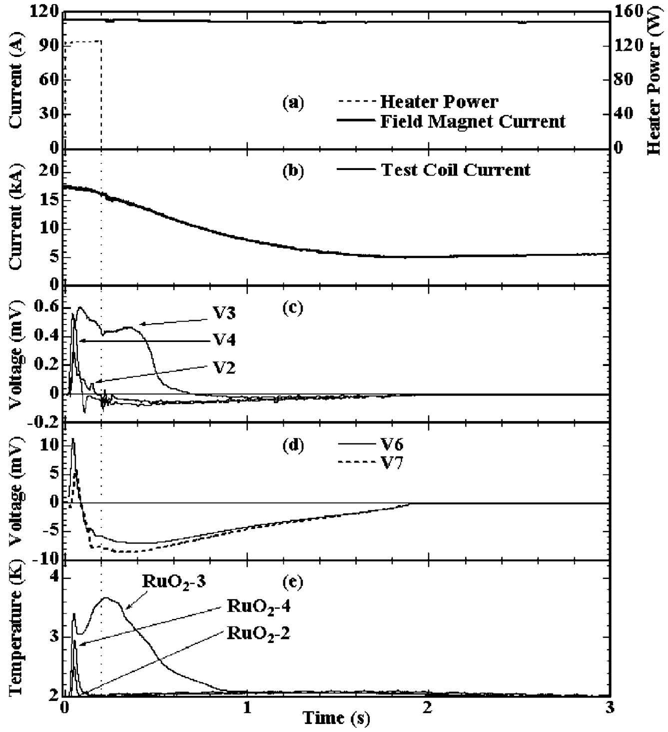

Fig. 6. Overall trends of the test results belong to Group III. $T_b = 2.0$ K, $B = 6.57$ T, $I = 17.4$ kA, $\Delta t = 200$ ms. (a) Field magnet current, (b) test coil current, (c) voltages between each taps, (d) voltages between each turns, (e) temperatures of the RuO_2 thermometers.

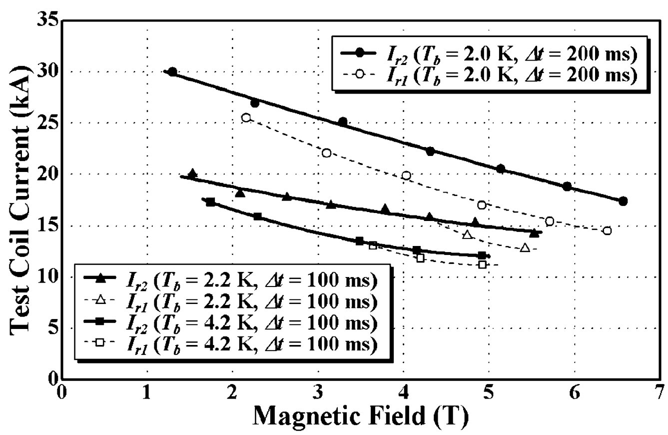

Fig. 7. Stability limit currents for the LHD test coil as a function of the magnetic flux density for the different liquid He temperature. For all the tests, input heater power was 125 W.

B. Stability of LHD Test Coil

The first recovery currents I_{r1} were defined as the maximum currents for the runs in Group I. The second recovery currents I_{r2} were defined as the maximum currents without the both-sides propagation of the normal zone. Fig. 7 shows the stability limit currents I_{r1} and I_{r2} versus the magnetic field for the different cooling conditions.

The current I_{r2} (solid lines) at a certain magnetic field became slightly larger for subcooled He (2.2 K) cooling than that for saturated He (4.2 K) cooling. It increased greatly in case of He II cooling (2.0 K). It is obvious that the He II cooling can improve the stability of the LHD conductor.

However, the dynamic one-side propagation of the normal zone (Group II) was observed with the current lower than I_{r2} mainly in case of He II cooling. It was observed only for the magnetic field density over 3.6 T in saturated He (4.2 K) cooling, and even in the low magnetic field region for He II (2.0 K) cooling. The dynamic one-side propagation would be dependent on the interaction of the magnetic field and the diffusion current into the aluminum stabilizer. Why the dynamic one-side propagation is observed even in the low magnetic field region for He II cooling will be explained as a result of the higher diffusion current accompanied with the higher transport current in the conductor. It is also considered that higher heat transport capacity of He II would be supporting the enlargement of the one-side propagation region to the higher current direction in case of He II cooling. The traveling normal zone for higher transport current would be cooled down immediately by the higher heat transport capacity of He II, and the both-sides propagation would be fairly suppressed. The cooling stability of the LHD helical coils would be improved by shifting to He II cooling.

IV. Conclusion

The adequacy of the current transformer method, which was used to supply the current of a few tens kA to the test conductor, was confirmed through the stability tests.

The stability limit under the certain magnetic field is slightly increased by shifting to subcooled He (2.2 K) cooling from saturated He (4.2 K) cooling. It is increased greatly by shifting to He II (2.0 K) cooling because of the high heat transfer capacity of He II. The advantages of the He II cooling on the cooling stability of the LHD conductor were confirmed.

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