Transient Stability of Large Helical Device Conductor With and Without Aluminum Stabilizer (1)—Experimental Results

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

***Abstract*—Stability tests were performed on two test coils wound with two kinds of large-scale composite superconductor, respectively. One is a original LHD conductor, which consists of a NbTi/Cu Rutherford cable, a pure aluminum stabilizer, and a copper sheath around the composite. Another is an Al-less test conductor, which is a LHD conductor without the aluminum stabilizer and a half of the copper sheath. This paper describes mainly on the latter Al-less test conductor comparing with the LHD conductor. The conditions of the tests were with the magnetic flux densities from 3 T to 7 T and at the bulk liquid helium temperatures 4.2, 2.2 K (sub-cooled He I) and 2.0, 1.8 K (He II) at atmospheric pressure. Asymmetrical normal zone propagation was observed even in the Al-less test conductor. The one-side propagation of the normal zone was also observed as was in the LHD conductor. The asymmetrical propagation is due not only to aluminum stabilizer but to the copper sheath and asymmetrical configuration. However, "traveling normal zone" observed in the LHD conductor was not seen in the Al-less test conductor. The current range for the one-side propagation is narrower than that for the LHD conductor. It is confirmed that the Al-stabilizer deeply affects the asymmetrical propagation.**

***Index Terms*—Aluminum stabilized superconductor, normal zone, superconducting coil, superfluid helium, transient stability.**

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 are now pool-cooled with 4.4 K liquid helium in the Phase I [1]. During the excitation tests of the LHD, the "dynamic one-side propagation" of a normal zone, which was initiated by a thermal disturbance, was observed in the helical coils [2], [3]. The initiated normal zone propagated only to one-side along the conductor. The normal zone with finite size separated from the initiated normal zone, and traveled along the conductor. Finally the "traveling normal zone" disappeared in a lower magnetic field area. This event occurred at a current and magnetic field slightly lower than the designed operation point, and it was not expected during the design stage of the LHD.

In the previous studies, the stability tests of the small LHD conductor coil were explained [4], [5], and advantage of He II cooling became clear compared with He I cooling. However the dynamic one-side propagation phenomenon was observed in wide current area below the quench current at the lower liquid helium temperature. Even if the dynamic one-side propagation occurs, the initiated normal zone will disappear in the lower magnetic field area and the coil will not quench. However, this phenomenon may lower the stable limit of the LHD helical coils when the higher excitation of the LHD magnet is realized by lowering the liquid He temperature. It is important that the mechanism of the dynamic one-side propagation is cleared and the normal zone behavior in the conductor immersed in sub-cooled He I and He II is investigated.

In this paper, in order to clarify the effect of the aluminum stabilizer on the transient stability of the LHD conductor and effect of Hall circulating current thought to cause asymmetrical propagation of normal zone, stability tests were performed by means of the conductor which eliminated a pure aluminum stabilizer from LHD conductor. The purpose of this study is twofold. First is to clarify the effect of the aluminum stabilizer on the transient stability of the LHD conductor at the normal transition. The transient stability of the conductor becomes worse compared to the steady-state one. This is due to the excess Joule heat generation caused by the delay of the current diffusion from the Rutherford cable into the aluminum stabilizer, whose electrical resistivity is very low. At the transient state, the thick aluminum may not effectively function as a stabilizer. Second is to investigate the asymmetrical normal zone propagation phenomenon. The propagation velocity of a generated normal zone shows asymmetry along the conductor. This phenomenon is peculiar to the LHD conductor, and will be caused by Hall current generation in the aluminum stabilizer and Rutherford cable.

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 litters. 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. Helium in this area was cooled down from 4.2 K to below λ-temperature at atmospheric pressure by the He II boiler through a heat exchanger. There is a superconducting

Manuscript received August 29, 2006. This work was supported in part by the NIFS (National Institute for Fusion Science), Japan under LHD Joint Research Project, and the Education Reform Plan for 21st Century.

R. Ikuta, M. Ohya, Y. Shirai, and M. Shiotsu are with the Department of Energy Science and Technology, Kyoto University, Kyoto 611-0011, Japan (e-mail: ikuta@pe.energy.kyoto-u.ac.jp).

S. Imagawa is with the National Institute for Fusion Science, Gifu 509-5292, Japan (e-mail: Imagawa@LHD.nifs.ac.jp).

Digital Object Identifier 10.1109/TASC.2007.898481

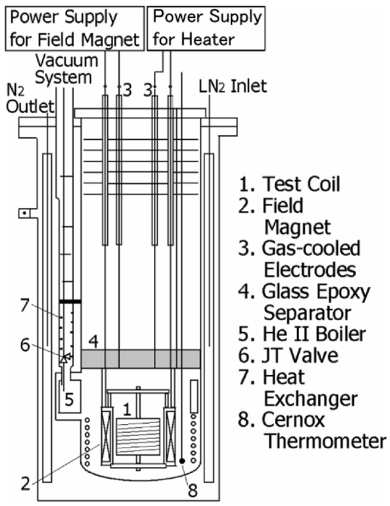

Fig. 1. Schematic diagram of the experimental setup.

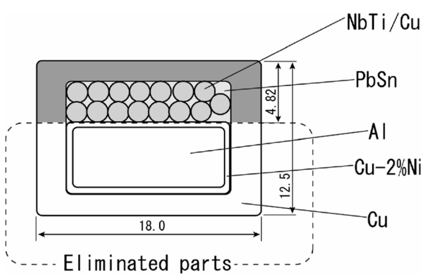

Fig. 2. Cross-sectional view of the test conductor.

magnet that imposes a 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 is 22.9 cm. It can generate a maximum of 7 T magnetic field in the center.

The test conductor consists of NbTi/Cu Rutherford cable, and a copper sheath. This conductor was made by eliminating the pure aluminum stabilizer and the CuNi clad from LHD conductor. The cross-sectional view of the test conductor is shown in Fig. 2. As it is the case with the LHD coil, a transformer type current supplying method was used [4], since it was not so easy to supply the transport current of dozens of kA to the test-conductor through the λ-plate.

Fig. 3 shows a photograph of the test-conductor coil. The test coil was wound with a test 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 supply method are given in [4]. The basic parameters of test coil are listed in Table I. The exposure ratio is the open area fraction of the insulation to admit coolant.

Fig. 4 shows the enlarged view of the test part (550 mm: 1 turn) and the layout of the voltage taps. The total length of the conductor is 4200 mm.

The test coil was thermally insulated by Kapton tape with interval of 55 mm to simulate the spacers of the LHD coil and the rate of exposure was set up to 67% for simulating the actual LHD helical coil condition. In the test part, a nichrome heater is

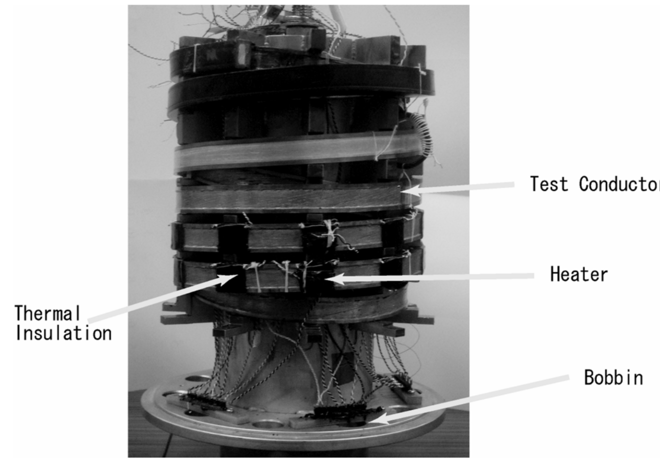

Fig. 3. Photograph of the test coil.

TABLE I
THE BASIC PARAMETERS OF TEST COIL

Test coil	
Conductor length	4746 mm
Coil radius	84.3 mm
Coil winding height	165.5 mm
Turn number	8
Thickness of Insulation	1.0mm
Interval of Insulation (Kapton Tape)	55 mm
Exposure ratio	67%

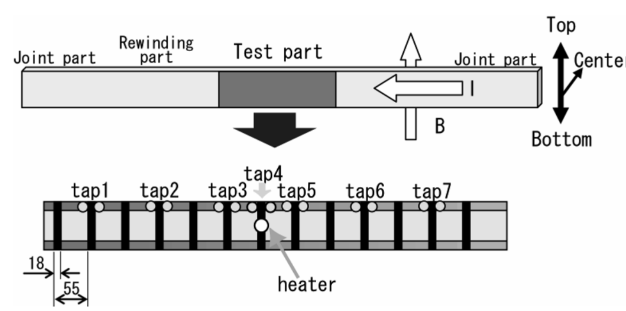

Fig. 4. Expanding diagram of the test conductor to the longitudinal direction.

fixed for origin of thermal disturbance and the voltage taps for observing normal zone propagation are set up around a heater along the test conductor (Fig. 4).

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 nucleation of a normal transition in the conductor.
3) Measure the tap voltage along the conductor to observe the behavior of the normal zone propagation.

The tests were performed at liquid He temperatures T_B of 4.2 K, 2.2 K (sub-cooled He I), 2.0 K, 1.8 K (He II) and for the magnetic flux densities B from 3.0 T to 7 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 upward originally (positive direction) and the test coil

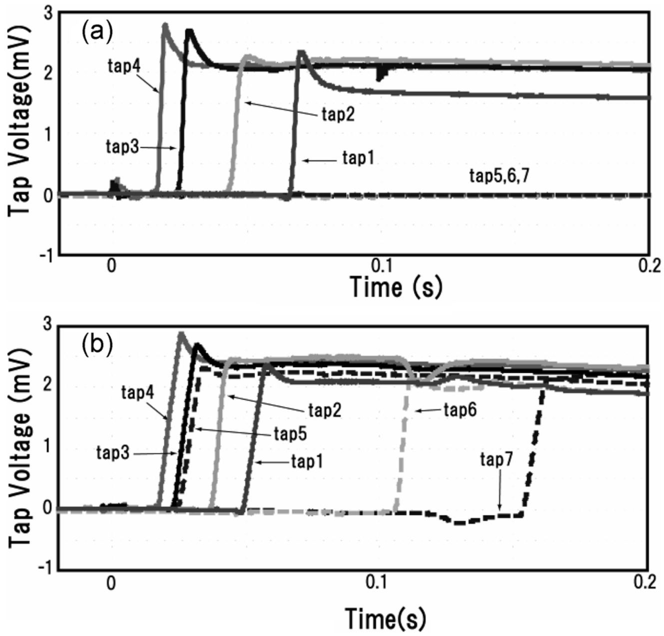

Fig. 5. Typical tap voltages at 2.0 K. (a) Group II one-side propagation ($B = 6.7$ T, $I = 14.9$ kA). (b) Group III both-side propagation ($B = 6.0$ T, $I = 16.5$ kA).

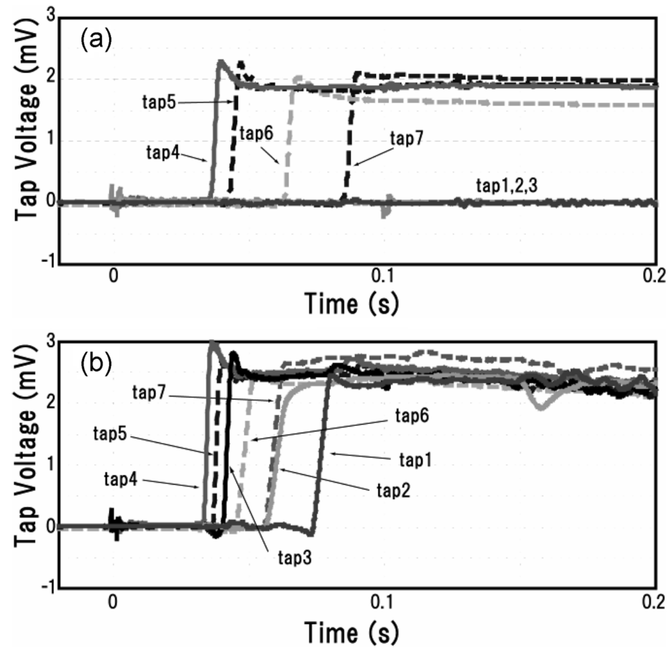

Fig. 6. Typical tap voltages with reverse magnetic field. (a) Group II one-side propagation ($B = -5.4$ T, $I = 17.5$ kA). (b) Group III both-side propagation ($B = -5.0$ T, $I = 22.9$ kA).

current flowed from the top to the bottom originally (in direction of tap7 to tap1 in Fig. 4: positive direction).

III. Results and Discussion

A. Typical Tap Voltage Waveforms

Characteristics of the transients after the addition of pulse heat input to the nichrome heater 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 across the taps. These tests were performed for the liquid temperature of 2.0 K.

(Group I) The normal zone arose only around the heater in response to the pulse heat input.

(Group II) As shown in Fig. 5(a), at $B = 6.7$ T, $I = 14.9$ kA, the voltages of tap 3, 2 and tap 1 arose in order. The initiated normal zone propagated to only one side (left hand side: downwards of the coil) along the conductor.

(Group III) As shown in Fig. 5(b), at $B = 6.0$ T, $I = 16.5$ kA, not only the voltages of tap 3, 2, 1, but the voltages of taps 5, 6, 7 rose in sequence. The initiated normal zone propagated to both sides along the conductor.

The one-side and both-side normal zone propagations observed for the LHD conductor [5] were also observed for the test coil without aluminum stabilizer. For the LHD conductor, the normal zone with a finite size separated from that of the heater section and propagates as "traveling normal zone". On the other hand, the normal zone observed here was continuous and was not the "traveling normal zone".

Fig. 6 shows the waveforms when the external magnetic field was applied on the conductor vertically downward $(-B)$ and the direction of the test coil current was not changed. We can see the one-side propagation to the opposite direction. The experimental results with $\pm B$ and $\pm I$ showed that the direction of the one-side propagation depends only on the direction of B but not on I.

This experimental result leads to the consideration that the Hall current asymmetrical distribution along the longitudinal direction causes the one-side propagation of the normal zone. When the normal zone appears in the LHD conductor, the transport current shunts to the Al stabilizer and Cu part, then the hall current begin to flow in the Al, Cu sheath and Cu part of Rutherford cable. The transport current flowing through Al and Cu parts has not only the longitudinal component but also the transversal one. At the both fronts of the normal zone, the Hall voltages due to the commutating currents (transversal component) to the Al or Cu sheath are in the opposite direction each other. At one front of the normal zone where the hall current has the same direction as the transport current, the Joule heat generation increases. At another front, the Hall current has opposite direction and the Joule heat generation decreases. It is considered, herewith, the one-side propagation phenomena occur. The Hall current direction can be changed by the polarity of B independent of I. Then, it can be said that the one-side propagation is due to the effect of Hall current.

B. Stability Test Results

Fig. 7 shows the stability test results for the liquid helium temperatures of 4.2 K, 2.2 K, 2.0 K and 1.8 K. Now the first minimum propagation current $Ip1$ 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 $Ip2$ is defined as the current above which a normal zone will propagate to both sides along the conductor. The $Ip2$ at a certain magnetic

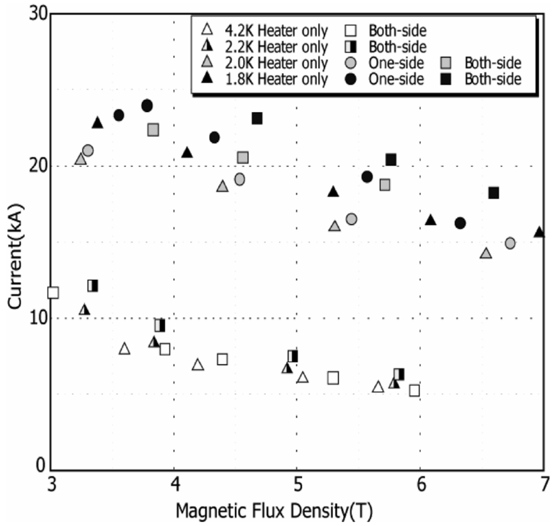

Fig. 7. Stability test results for test coil at 4.2, 2.2(He I) 2.0 K, and 1.8 K (He II).

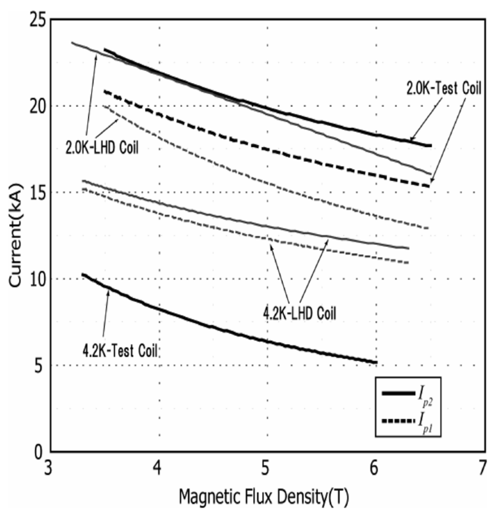

Fig. 8. Comparison of the stability test results for test conductor with LHD conductor.

field becomes slightly higher with the decrease of liquid helium temperature from 4.2 K down to 2.2 K, and it increases greatly by a change of the cooling mode from He I to He II.

Fig. 8 shows the fitted curves of $Ip1$ and $Ip2$ obtained here in comparison with those for the LHD conductor coil [5]. It should be noted that the $Ip2$ in 4.2 K cooling is about 60% of that for the LHD conductor. This will be due to the decrease in the steady stability margin caused by the cut of the aluminum stabilizer. On the contrary, the current $Ip1$ and $Ip2$ for the test conductor with HeII cooling are slightly higher than those for the LHD conductor, respectively. As the Rutherford cable is directly cooled with He II, this will be due to the super cooling characteristics of He II for transient heat transfer.

The current range for the one-side propagation (between $Ip1$ and Ip) was smaller than that for LHD conductor. It is considered that the Al-stabilizer deeply affects the asymmetrical propagation.

IV. Conclusions

The stability tests in He I or He II cooling were performed by using the test coil wound with the LHD conductor eliminated the pure aluminum stabilizer. Experimental results lead to the following conclusions.

Characteristics of the transients after the pulse heat input to the nichrome heater were classified into the following thee groups depending on the magnetic flux density and the test coil current. (Group I) Non-propagation, (Group II) one-side propagation, (Group III) Both-side propagation.

One-side propagation was observed even without the Al-stabilizer. Hall current of the copper sheath may cause the asymmetrical heat generation. The asymmetrical propagation is due not only to aluminum stabilizer but to the copper sheath and asymmetrical configuration.

However the range of the transport current for the one-side propagation was smaller than that for LHD conductor. It is confirmed that the Al-stabilizer deeply affects the asymmetrical propagation.

The "traveling normal zone" observed in the LHD conductor, was not seen in the Al-less test conductor. The normal zone is stationary and does not diminish. The steady state stability becomes worse without Al-stabilizer.

The minimum both-side propagation current in 4.2 K cooling is about 60% of that for the LHD conductor. This will be due to the decrease in stability margin. On the contrary, in He II cooling, the minimum one-side propagation current for the test conductor are slightly higher than or almost in agreement with those for the LHD conductor. As the Rutherford cable is directly cooled with He II, this will be due to the super cooling characteristics of He II for transient heat transfer.

The one-side propagation direction depends on the direction of the magnetic field, but the transport current. It is confirmed that the one-side propagation is due to the effect of Hall current.

References

[1] S. Imagawa, N. Yanagi, and H. Chikaraishi *et al.*, "Results of the first excitation of helical coils of the large helical device," *IEEE Trans. Appl. Supercond.*, vol. 10, pp. 606–609, 2000.

[2] N. Yanagi, S. Imagawa, and T. Mito *et al.*, "Asymmetrical normal-zone propagation observed in the aluminum-stabilized superconductor for LHD helical coils," *IEEE Trans. Appl. Supercond.*, vol. 10, pp. 610–613, 2000.

[3] N. Yanagi, S. Imagawa, and T. Mito *et al.*, "Analysis on the cryogenic stability and mechanical properties of the LHD helicalcoils," *IEEE Trans. Appl. Supercond.*, vol. 12, pp. 662–665, 2002.

[4] A. Higuchi, M. Ohya, Y. Shirai, M. Shiotsu, and S. Imagawa, "Cooling stability test of He II cooled LHD conductor(1)—current supply and measuring method," *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 1443–1446, 2004.

[5] M. Ohya, A. Higuchi, Y. Shirai, M. Shiotsu, and S. Imagawa, "Cooling stability test of He II cooled LHD conductor(2)—experimental results," *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 1443–1446, 2004.