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# Improvement in Cryogenic Stability of the Model Coil of the LHD Helical Coil by Lowering the Temperature

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***Abstract*—Helical coils of the Large Helical Device are pool-cooled superconducting magnets, in which propagation of a normal-zone has been observed several times at about 86% of the nominal current of 13.0 kA. It is planned to improve the cryogenic stability by lowering the inlet temperature. In order to estimate the effect, the cryogenic stability of a model coil of the helical coil was examined in saturated and subcooled helium. Liquid helium is supplied from the bottom of the model coil, and it is exhausted through the winding to the current-leads tank. The inlet helium is subcooled by a pre-cooler. A normal zone was initiated by a heater on the conductor at the bottom of the coil. In saturated helium of 4.4 K and 0.12 MPa, the minimum current to propagate over the next turn varies from 10.7 to 11.2 kA in the four cases that are without or with additional thermal shields, and before or after being subcooled. The difference is considered to be caused by the change of quality of saturated helium inside the winding or by the change of the wetted condition of the conductor surface. The minimum currents are higher at the lower temperatures in subcooled helium. It is raised up to 11.7 kA at 3.5 K of the temperature inside the winding. The propagation velocity at each minimum current is almost same. Namely, the propagation velocities at the same current are slower at the lower temperature in subcooled helium.**

***Index Terms*—Aluminum stabilizer, dynamic stability, minimum propagating current, subcooled helium.**

## I. INTRODUCTION

HELICAL coils of the Large Helical Device (LHD) are pool-cooled superconducting magnets. They have been operated below 86% of the design current of 13 kA because a normal-zone has propagated several times at almost the same current [1]. It was recovered except for the fourth propagation at 11.45 kA. By a novel detection system of propagation with pick-up coils along the helical coils, it is known that all the 10th to 17th normal-zones were initiated at the bottom position of the coil and propagated to only the downstream side of the current. The propagation was stopped at the upper position, where the field is lower than at the bottom. Liquid helium is replenished from ten bottoms of the coils, and it flows through mainly two channels at both the outer corners of the coil case. On the other hand, helium bubbles rise in the winding by the buoyancy. Since the channels at the inner corners of the coil case are very narrow, the cooling condition of the innermost layer might be deteriorated at the bottom of the coil where the bubbles are apt to be accumulated.

TABLE I
SPECIFICATIONS OF THE MODEL COIL

| Item | Design values |
|---|---|
| Maximum field in coil | 6.9 T at 13.0 kA |
| Winding number | 24 turns × 12 layers |
| Inner radius of the innermost layer | 200 mm |
| Conductor size | 18.0 mm × 12.5 mm |
| Gap between turns / Layers | 2.0 / 3.5 mm |
| Conductor length | 550 m |
| Inductance | 29 μH |
| Weight of conductor / case | 0.86 / 1.7 ton |

It is planned to improve the cryogenic stability by lowering the inlet temperature. In order to estimate the effect, a model coil was made of the same conductor as the helical coil [2]. The first cool-down and stability tests were carried out without a thermal shield on the coil. In the second cool-down, a thermal shield with multi-layer insulators was added to reduce the heat load to a coil. Furthermore, the third cool-down and stability tests were carried out to examine uncertainty of stability in saturated helium and to confirm the reproducibility in subcooled helium.

## II. MODEL COIL AND EXPERIMENTAL SETUP

A conductor of the LHD helical coil consists of NbTi/Cu strands, a pure aluminum stabilizer, and a copper housing. It is known that a normal-zone can propagate dynamically below the cold-end recovery current by additional heat generation due to the slow current diffusion into the thick stabilizer [3]. Specifications and the schematic drawing of the model coil are shown in Table I and Fig. 1. The conductor, same as the LHD helical coil, was wound on a thick coil case by layer winding of 24 turns and 12 layers. Electrically insulating spacers, thickness and width of which are 3.5 and 17 mm, are settled on the inner ring by the pitch of 54 mm, as shown in Fig. 2. The wetting surface fraction of the first layer is 67%. The highest magnetic field occurs at the middle turn of the first layer, which is the testing region for the cryogenic stability. The value is 6.9 T at 13 kA, the same as the middle turn in the first layer of the LHD helical coil.

The propagation of a normal-zone were detected by voltage taps that were attached on the side plane of the conductor to exclude the effect of the shift of the current center from superconducting cable to the aluminum stabilizer during a normal-zone propagation. Tape heaters are inserted between the outer plane of the conductor and the layer-to-layer spacer to initiate a normal-zone. Thermo-sensors are installed in the cryogen to

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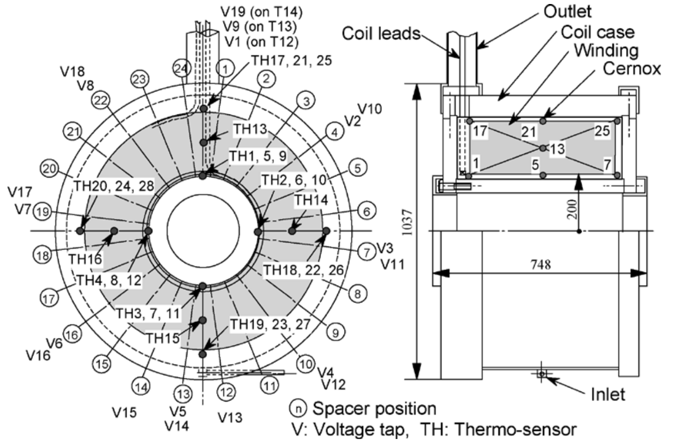

Fig. 1. Schematic drawing of the model coil. Voltage taps of V1 to V8 are on the 12th turn, and V9 to V18 are on the 13th turn.

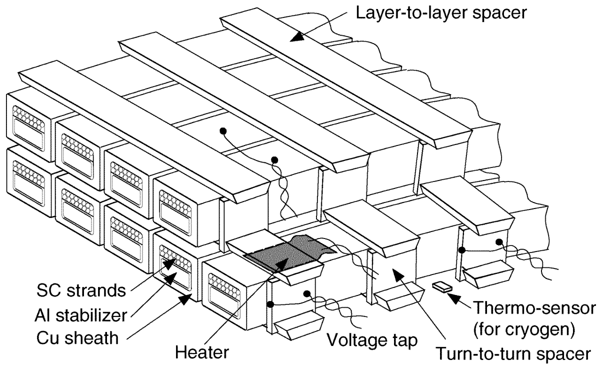

Fig. 2. Schematic drawing of the winding and sensors of the model coil.

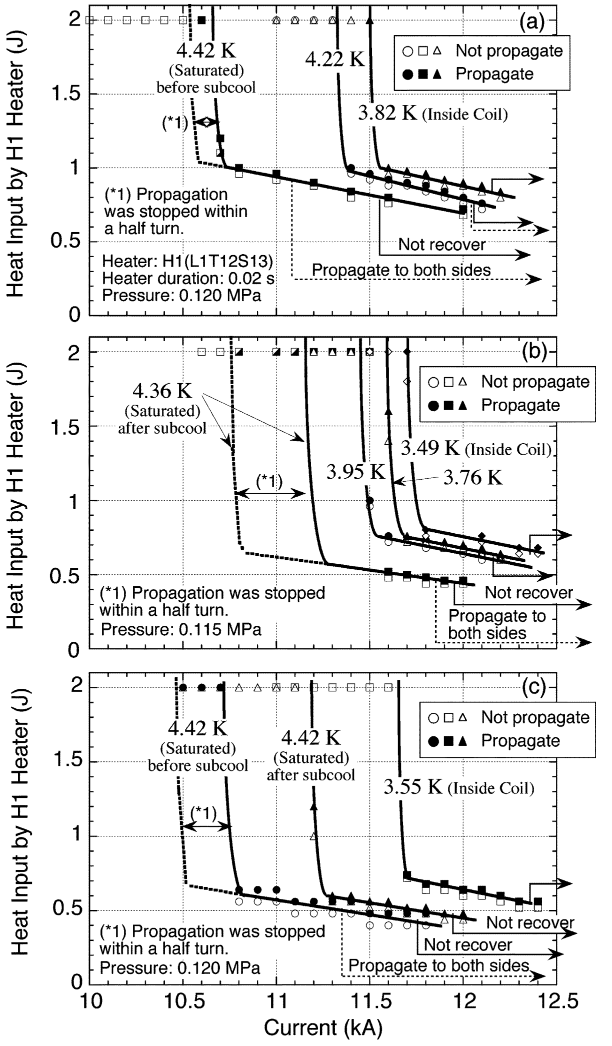

Fig. 3. Minimum heat input for the propagation of a normal-zone in the model coil in (a) the first, (b) the second, and (c) the third cool-down. The open or closed symbol means without or with propagation, respectively.

examine the temperature distribution of subcooled helium in the coil, as shown in Fig. 1.

The inlet and outlet pipes for cryogen are located at the bottom and top of the model coil case, respectively. Although the diameter of the inlet pipe is 10 mm, a wide aperture of 20 mm × 250 mm is drilled in the outer ring. The outlet pipe of the diameter of 100 mm is connected to a header tank. A pair of coil-leads passes through the outlet pipe. The inlet helium is subcooled to 3.0 K by a pre-cooler. In the first cool-down the model coil was not covered with any thermal shields to simulate the LHD helical coil. However, the estimated heat load to the coil was as much as 20 W due to the delay of cool-down of an inner vessel of the cryostat [2]. The heat load was reduced to less than 7 W in the second and the third cool-down by being covered with a thermal shield of copper plate with multi-layer insulators.

Normal-zones were initiated by the tape heater inserted between the conductor and the spacer. The heating duration is set to 20 ms to put as much energy as possible adiabatically. The heater at the bottom of the middle turn of the first layer was used. Firstly, the minimum current for a normal-zone propagating more than the next voltage tap was surveyed with the maximum heating power of 100 W. After that, the minimum heater power was surveyed by 100 A steps.

## III. EXPERIMENTAL RESULTS

Results of the stability tests in the first and second cool-down are shown in Figs. 3(a) and 3(b). At a current close to the minimum current to begin propagation, a normal-zone propagated to only the downstream side of the current [4]. At higher currents, a normal-zone propagated to both sides. The upstream propagation velocity is almost half as downstream. At the lower temperature, that is, at larger degree of subcooling, the minimum currents for propagation are higher, and necessary heat inputs for initiating a normal-zone are larger. On the other hand, the stability in saturated helium in the second cool-down was greatly improved as compared to the first cool-down. The current for propagating over the next turn was increased up to 11.2 kA from 10.7 kA, and the minimum current for propagating to both sides was also increased up to 11.9 kA from 11.1 kA. The reason was considered to be reduction of steady heat loads by addition of the thermal shield. Nevertheless, the history of testing temperatures was also different. While the stability tests in saturated helium were carried out at first

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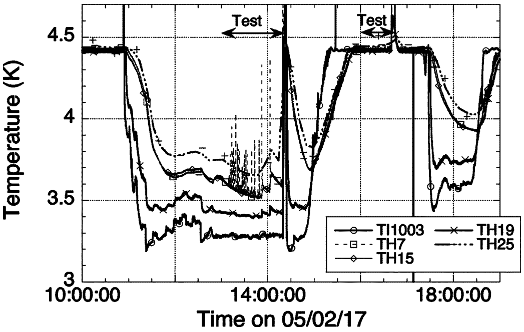

Fig. 4. Temperatures in the model coil in subcooled and saturated helium. TI1003 is the temperature at the inlet pipe to the model coil. TH19 and TH25 are the temperatures near the inlet and outlet, respectively.

in the first cool-down, they were carried out with raising the temperatures from 3.5 K in the second cool-down.

In order to examine the effect of temperature history, the stability in saturated helium was examined before and after subcooling to 3.5 K in the third cool-down. The stability test before subcool was carried out 20 hours after being immersed in liquid helium. It was sufficient time to cool-down the coil, because the temperature time constant is less than 100 s even for the thick case of stainless steel. The test after subcool was carried out after all thermo-sensors in the coil had indicated 4.4 K, as shown in Fig. 4. The test results are shown in Fig. 3(c). The stability after subcool was obviously better than that before subcool. The latter is almost same as that in the first cool-down, even though the steady heat load is decreased to one third. It means that the deterioration of heat transfer before subcool is caused not only by the heat load. Although the cause is not understood well, it should be thought that the wetted condition of the conductor surface might be improved by being subcooled once.

In saturated helium, there is a range of the current where a normal-zone induced at the bottom propagates and stops within a half turn. This means that the heat transfer from the tested layer is worse around the bottom of the coil. The range was the widest in the case of the second cool-down, while it was not observed in the case of 'after subcool' in the third cool-down. The former data were obtained about one hour after being raised up to the saturated temperature from 3.95 K. The latter data were obtained just after being raised up to the saturated one from 3.55 K. Consequently, the heat transfer will be improved in the whole area of the winding just after being subcooled, and it will be gradually deteriorated from the area where bubbles gather. Since the channels along the conductors are restricted by the spacers between them, bubbles move to the highest position in each cross-section of the coil by the buoyancy. Concerning the tested layer bubbles are apt to be accumulated at the lower half of the coil, especially at the bottom of the coil.

Examples of output of the voltage taps are shown in Fig. 5 for the current of 11.3 kA in saturated helium before and after subcool. After subcool, the propagation velocity and recovery time became slower and shorter, respectively, in spite of the same peak voltage. It proves that heat transfer is improved after subcool. Average propagation velocities are shown in Fig. 6. Their reproducibility is fairly good, and that in subcooled helium seems to depend on only the temperature.

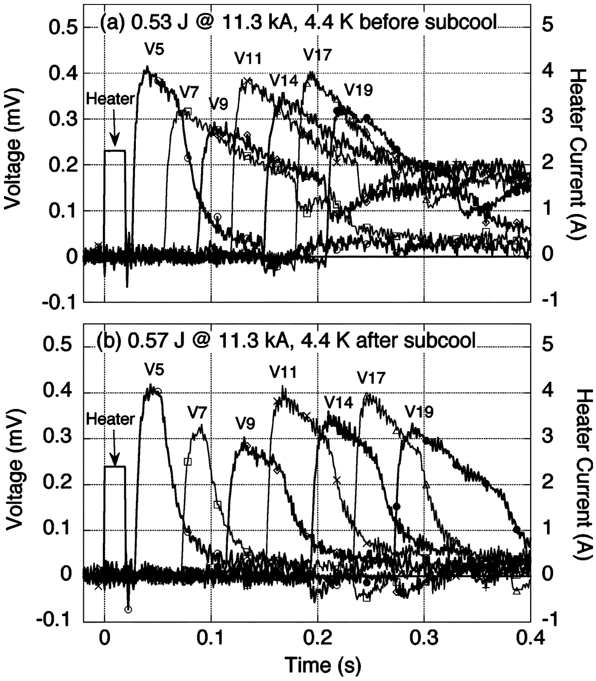

Fig. 5. Output of voltage taps during propagation of a normal-zone at 11.3 kA in saturated helium (a) before and (b) after subcool. The normal-zone propagated to only the downstream side of the current with recovery.

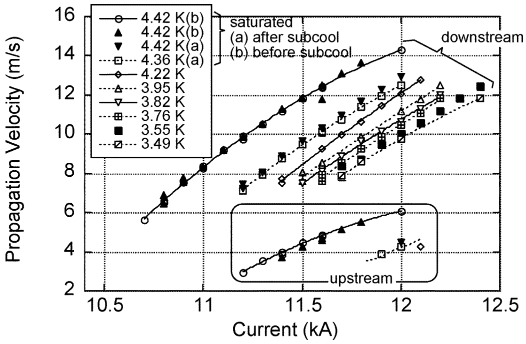

Fig. 6. Propagation velocity of the model coil in the first (solid lines), the second (dashed lines), and the third (close symbols) cool-down.

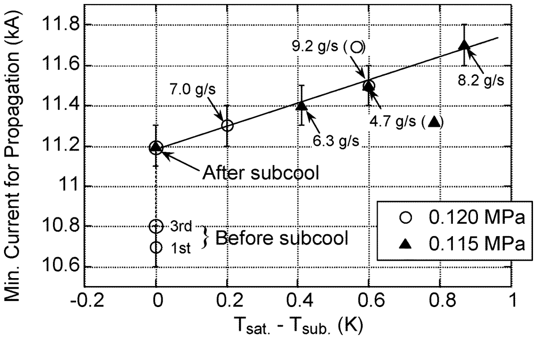

Fig. 7. Increase of the minimum currents for propagating over a half turn of the model coil with the degree of subcooling.

## IV. DISCUSSION

In subcooled helium the increment of the minimum currents to begin propagation is almost proportional to the degree of subcooling, as shown in Fig. 7. Since the minimum current in

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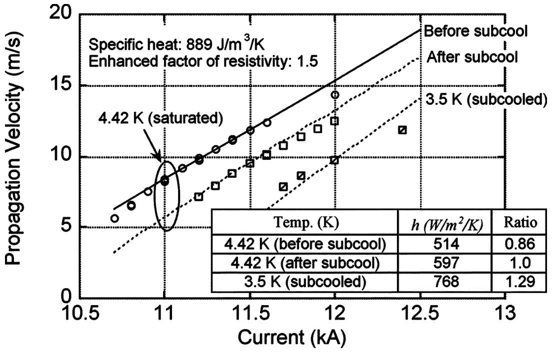

Fig. 8. Calculated propagation velocity of the model coil.

saturated helium after subcool is on the extrapolated line from subcooled helium, its condition must be similar to subcooled helium. The good condition continued at least a few hours and even after the coil quench except for the local area at the bottom of the coil, where the minimum currents must be decreased with the worse quality, that is the higher ratio of gas against the total, of saturated helium.

From the quasistatic heat balance equation, the propagation velocity $v_g$ is expressed as

$$v_g = \sqrt{\frac{phk}{A}} \frac{\Gamma - 2}{F \cdot c\sqrt{\Gamma - 1}} \tag{1}$$

$$\Gamma = \frac{\rho I^2}{Aph\left(\frac{T_c + T_s}{2} - T_b\right)} \tag{2}$$

where $p$, $A$, $h$, $k$, $\rho$, $c$, $I$, $T_{\mathrm{c}}$, $T_{\mathrm{s}}$, $T_{\mathrm{b}}$, $F$ are the perimeter, the cross-sectional area, the equivalent heat transfer coefficient, the thermal conductivity, the resistivity, the specific heat, the current, the critical temperature, the current sharing temperature, the bath temperature, and the enhanced factor of the average resistivity due to slow current diffusion, respectively. While $k$ and $c$ are extensively changed at low temperatures, they are assumed constant in this calculation. The values of $F$, $c$, and $h$ were surveyed to fit the experimental results with $k$ of 1,000 W/m/K. Fig. 8 shows the calculated result for $F$ of 1.5 and $c$ of $889\mathrm{J/m^3/K}$ that corresponds overall heat capacity of the conductor at 4 K. It shows that the equivalent heat transfer in saturated helium is improved by more than 10% after being subcooled. Furthermore, it is improved by 30% by being subcooled to 3.5 K. Its value is considered to be correlated to the increment of critical heat flux of nucleate boiling in subcooled helium [5], [6].

## V. SUMMARY

The cryogenic stability of the model coil, the conductor of which is same as the LHD helical coil, was examined in saturated and subcooled helium. In subcooled helium the minimum current for propagation of a normal-zone is almost proportional to the temperature decrease from the saturated temperature. The improvement rate of equivalent heat transfer is estimated to be 30% for being subcooled from 4.4 K to 3.5 K. On the other hand, the equivalent heat transfer in saturated helium was improved by more than 10% after being subcooled once. The good condition continued even after a coil quench that induced a temperature rise. While the cause is not understood well, the wetted condition of the conductor surface should be improved by being subcooled once. Gaseous helium might be remained in narrow spaces between the conductors and the spacers by only being immersed in saturated helium even for a sufficient time against the temperature time constant of the coil.

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