Results of the Excitation Test of the LHD Helical Coils Cooled by Subcooled Helium

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S. Imagawa, T. Obana, S. Hamaguchi, N. Yanagi, T. Mito, S. Moriuchi, H. Sekiguchi, K. Ooba, T. Okamura, A. Komori, and O. Motojima

***Abstract*—Large Helical Device, the largest superconducting stellarator, has been operated for the research of fusion plasma since 1998. The toroidal field of almost 3 T is produced by a pair of pool-cooled helical coils, in the innermost layers of which a normal-zone had been induced several times at the bottom of the coil at higher currents than 11.0 kA. Since the field is not the highest there, the local cooling conditions are probably deteriorated by bubbles gathered by buoyancy. In order to improve the cryogenic stability by subcooling, an additional cooler with two-stage cold compressors was installed at the inlet of the coil in 2006. The inlet and outlet temperatures of the coils were successfully lowered to 3.2 K and 3.8 K, respectively, with a mass flow of 50 g/s. In spite of a half charging rate to reduce AC losses, a normal-zone was induced near the top of the coil at 11.45 kA. It propagated to one side and stopped near the inner equator, where the field is the highest. In comparison with the stability tests with a model coil, the local temperatures of the innermost layers near the top is considered to have been raised up to almost the saturated temperature of 4.4 K by charging. The excitation method was revised to waiting cool-down at 11.0 kA, and the excitations up to 11.5 kA have been attained.**

***Index Terms*—Loss measurement, pool-cool, propagation of a normal zone, stability, subcooled helium.**

I. Introduction

LARGE HELICAL device (LHD) is a experimental device for the research of fusion plasma. A pair of helical coils of LHD is the world's largest pool-cooled superconducting magnets that have been operated since 1998. Their operation currents were limited less than 11.0 kA in spite of the design current of 13.0 kA, because a normal-zone has propagated several times at almost the same current [1]. Propagation of a normal-zone had been observed 17 times in the helical coil until 2005. A normal-zone induced by conductor motions can propagate at higher currents than 11.0 kA in saturated helium at 4.4 K. The induced positions can be detected with pickup coils that were installed along the helical coils in 2001 [1]. Since then, propagation of a normal-zone had been observed eight times. The helical coil is divided into three blocks, H-I, M, and O from the inside, as shown in Fig. 1. All the normal-zones were induced in the H-I block at the bottom of the coil. Since the field is not the highest at the bottom, the local cooling condition will be deteriorated by bubbles gathered to the H-I block by buoyancy.

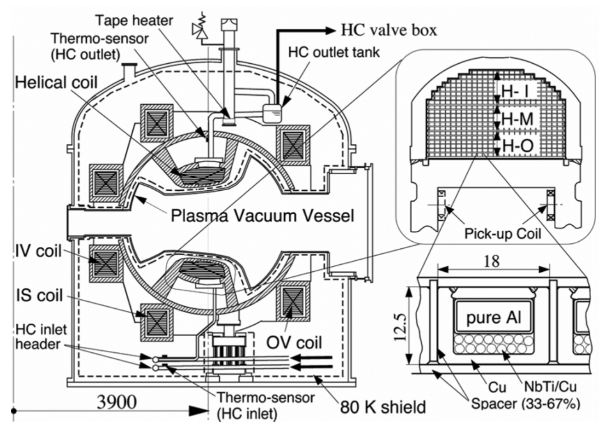

Fig. 1. Cross-section of the LHD cryostat and the helical coils, in which spacers are inserted between conductors with a pitch of 55 mm.

In order to improve the cryogenic stability, an additional heat exchanger with two-stage cold compressors was installed at the inlet of the helical coils. When the bath temperature of the heat exchanger is 3.0 K and the mass flow is 50 g/s, the inlet and outlet temperatures of the coil were successfully lowered to 3.2 K and 3.8 K, respectively, from the saturated temperature of 4.4 K [2]. The average temperature of the winding is estimated at about 3.6 K [3]. According to the results of stability tests with a model coil cooled by subcooled helium, the helical coils were expected to be excited up to almost 12 kA without propagation of a normal-zone [4].

This paper intends to summarize the first excitation tests of the LHD helical coil cooled by subcooled helium. Firstly, a temperature rise by excitation is evaluated, because it is needed to maintain low temperatures for better heat transfer. The next, the results of the excitation tests are investigated.

II. AC Losses of Helical Coil

Liquid helium is supplied from ten positions at the bottom of the two helical coils through two inlet-headers, and it is taken out from ten top positions to an outlet tank. The positions of the thermo-sensors are shown in Fig. 1. An example of the temperature changes under the subcooling operation is shown in Fig. 2. When the temperature of the heat exchanger was lowered to 3.0 K by raising the round speed of the cold compressors, the inlet temperatures of the helical coils were rapidly lowered to 3.2 K with the mass flow of 50 g/s. The outlets were gradually lowered to 3.8 K with the time constant of about 2 hours, which

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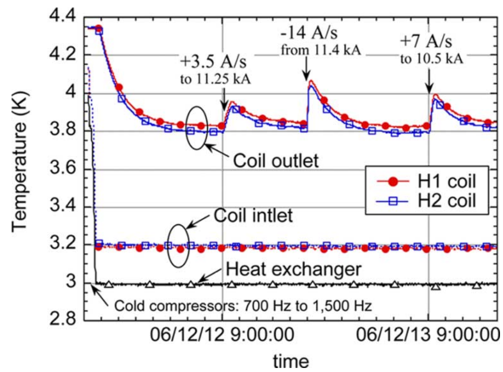

Fig. 2. Inlet and outlet temperatures of the helical coils under the subcooling operation. The mass flow were almost 50 g/s. Coil currents were maintained at 11.4 kA and 11.0 kA during the day time on 12/12 and 12/13, respectively.

TABLE I
STEADY HEAT INPUTS TO THE LHD HELICAL COILS

HC temperature (K)		Mass flow	Heat input	Date
Inlet	Outlet	(g/s)	(W)	
3.48	4.04	42.8	89.5	'06/11/14
3.48	4.01	45.2	89.1	'06/11/15
3.20	3.84	44.7	93.3	'06/11/16
3.02	3.81	47.3	95.2	'06/12/12
3.19	3.80	49.2	96.1	'06/12/19

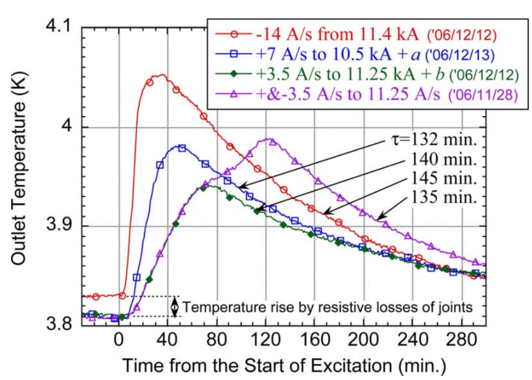

Fig. 3. Temperature rises at the outlet of helical coil by excitation, where a is "$+1.4$ A/s to equivalent 11.1 kA", and b is "$+0.7$ A/s to equivalent 11.5 kA."

corresponds to the time to replace the helium in the coils. The inventory is 1.2 m^3 per coil. When the cryogen is subcooled, heat inputs can be estimated from the enthalpy increase from the coil inlet to the outlet. The steady heat input to the coils is estimated at 95 W, when the outlet temperature is about 3.8 K, as shown in Table I. The steady heat input seems to be slightly less at the higher temperature of the coil. Also, the steady heat input to the inlet connecting pipes is estimated at 20 W.

Temperature rises at the coil outlet in charging by three kinds of ramp rates are shown in Fig. 3. The enthalpy at the outlet after the excitation can be fitted by exponential function. It means that the temperature of the helium in the coils is much averaged by the thermal conductivity of the conductors and the natural

TABLE II
COUPLING AND HYSTERESIS LOSSES OF HELICAL COILS FOR VARIOUS RAMP RATES OF THE CURRENTS

Ramp rate	AC losses [kJ]		
	Total	Coupling (cal.)	Hysteresis
-14 A/s from 11.4 kA	466	306	160
+7 A/s to 10.5 kA $+a$	299	143	156
+3.5 A/s to 11.25 kA $+b$	235	76	159
+-3.5 A/s to 11.25 kA	431	152	279 (+ and -)

(note) a and $b$are same as Fig. 3.

convection. In this case, an additional heat load by the excitation can be expressed by

$$
\begin{aligned}
Q_{AC} &= \int_0^{\infty} (\Delta H(t) \cdot m - q_R(t))\, dt \\
&= \int_0^{t_1} (\Delta H(t) \cdot m - q_R(t))\, dt \\
&\quad + (\Delta H(t_1) \cdot m - q_{R0}) \cdot \tau
\end{aligned}
\tag{1}
$$

where Q_{AC}, q_R, q_{R0}, ΔH, m, τ and t_1 are AC losses, the resistive heating power of joints, that at the constant current after charging, the increase of enthalpy at the outlet by the excitation, the mass flow rate, the time constant of the enthalpy decreasing after charging, and any time in the period of the enthalpy decreasing by τ, respectively. q_{R0} is estimated at 3 W at 11.4 kA from the asymptotic value of ΔH during the excitation with the constant current. AC losses estimated by (1) are listed in Table II. The AC losses are divided into coupling losses and hysteresis losses. The former is in proportion to a ramp rate when it is sufficiently slow against the time constant of the coupling loop, and the latter is independent of it. In addition, the former is independent of the temperature below about 10 K, because the conductivity of the materials is constant. Eddy current losses of the coil-cases are included in the coupling losses in this evaluation. The time constant of overall coupling currents in the conductor had been measured [5]. Eddy current losses of the coil-cases can be estimated by their mutual inductance to the helical coil. Hysteresis losses can be derived by subtracting the calculated coupling losses from the measured losses, as shown in Table II. The evaluated hysteresis losses are reasonable, because they are independent of the ramp rate.

The critical current density at the zero field, j_{c0}, of the superconductor in subcooled helium is estimated at 1.5×10^{10} A/m^2 by using Kim model [6] to fit the data in Table II. The j_{c0} at saturated temperature of 4.4 K is estimated at 0.9 to 1.0×10^{10} A/m^2 from the measurement of residual magnetic field [7]. Since the hysteresis loss is in proportion to the critical current, the loss in subcooled helium is about 1.5 times higher than in saturated helium. Even in slow charging with the ramp rate of 3.5 A/s, the AC loss power is 72 W in which the hysteresis losses occupy 2/3 of the total losses.

III. FIRST RESULTS OF EXCITATION TEST

Excitation tests of the helical coils cooled by subcooled helium were carried out while controlling an increase of the outlet temperatures within 0.15 K by slow charging rate of 3.5 A/s to

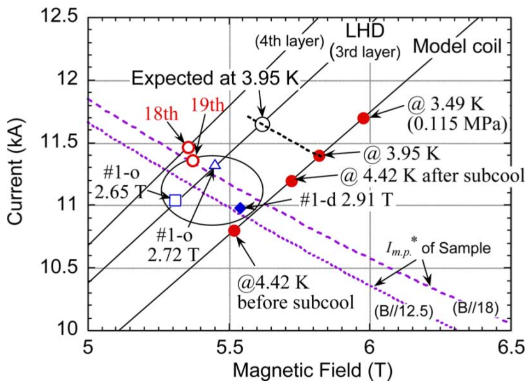

Fig. 4. Minimum current for a normal-zone propagating in the LHD helical coil and the model coil. The maximum field in the last turn of the third layer is used for the LHD helical coil.

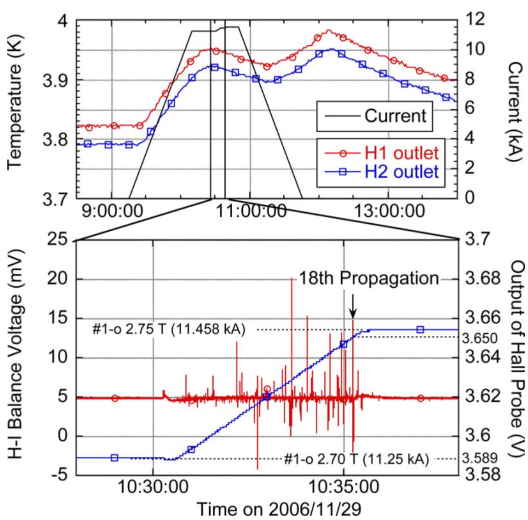

Fig. 5. The outlet temperature, the balance voltage, and the magnetic filed at the first excitation to the higher currents on '06/11/29. The 18th propagation of a normal-zone was occurred at #1-o 2.747 T (11.45 kA).

11.25 kA and 0.7 A/s after that. According to the results of stability tests in the model coil [5], as shown in Fig. 4, the LHD helical coil could be excited up to 11.6 kA without propagation of a normal-zone, even if the temperature of the helium in the coil was same as the outlet temperature. Nevertheless, a normal-zone was induced in the H2-I block at 11.45 kA in the first excitation test to the higher currents. The H2 coil outlet temperature was 3.92 K at that time, as shown in Fig. 5. The normal-zone must have been induced by a large conductor motion in charging. The induced position is near the top of the eighth in ten toroidal sectors. It has propagated to one side and stopped near the inner equator, where the field is the highest. The ripple of the field in a pitch is about 0.4 T. Its propagation length was only 2 m. It was the 18th propagation of a normal-zone since the beginning of operation. The inducing position and the currents for the normal-zones are listed in Table III. The position is quite different. When the coil was cooled by saturated helium, all the normal-zones were induced at the bottom. On the contrary, they were induced at the top in the subcooling condition.

In this cooling cycle, propagation of a normal-zone was observed again at the almost same current in the first excitation

TABLE III
PROPAGATION OF NORMAL-ZONES IN THE LHD HELICAL COILS SINCE 2001

No.	Mode	H-O/M/I current (kA)	Coil	Position
10th	#1-c_R4.1 m	11.16/ 11.16 / 11.16	H1-I	#10 bottom
11th	#1-o_γ1.258	11.71/ 11.57/ 10.94	H1-I	#10 bottom
12th	#1-o	11.04/ 11.04 / 11.04	H1-I	#10 bottom
13th	#1-o	11.15/ 11.15 / 11.15	H1-I	#10 bottom
14th	#1-d	11.30/ 11.30 / 11.30	H1-I	#10 bottom
15th	#1-c	-11.08/ -11.08 / -11.08	H2-I	#5 bottom
16th	#1-o	-11.11/ -11.11 / -11.11	H2-I	#5 bottom
17th	#1-c_R4.0 m	11.00/ 11.00 / 11.00	H1-I	#10 bottom
18th	#1-o	11.45/ 11.45 / 11.45	H2-I	#8 top
19th	#1-d_R3.65 m	-11.75/ -11.35/ -11.35	H1-I	#3 top

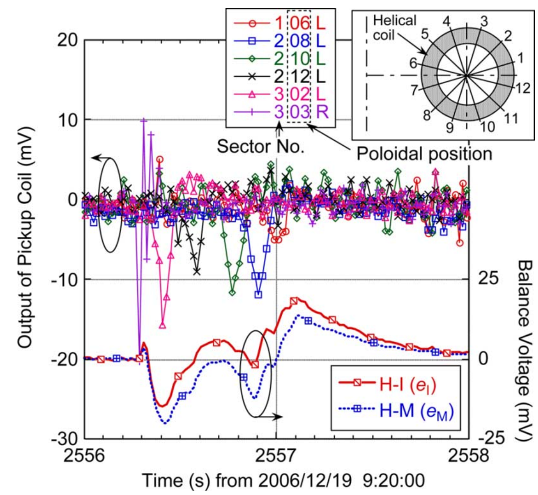

Fig. 6. Balance voltage of the helical coils and output of pickup coils during the 19th propagation of a normal-zone. The sector number means the toroidal position, and 1st and 6th are located at north and south, respectively.

after the polarity was changed. It was induced in the H1 coil. The outputs of the pick-up coils for the 19th normal-zone are shown in Fig. 6. It was also initiated near the top and propagated to one side that is opposite direction to the 18th one. The propagation was almost stopped near the outer equator, but it continued to propagate and finally stopped near the inner equator. It suggests that the temperature of cryogen around the innermost layers would be raised at restricted area, probably at top and bottom.

Fig. 7 shows resistive components in the balance voltages. It can be derived by integrating the H-M balance voltage that detects a current shift in the conductor by propagation of a normal-zone in the H-I block [1]. Also, it can be derived by subtracting the H-M voltage from the H-I one. The fitting parameter for the subtraction is related to the cross-sectional position of the conductor in which the normal-zone propagated. The value of 1.2 suggests that the conductor will be the first turn in the fourth layer. From Fig. 4, the local temperature of the innermost layers near the top is considered to have been raised up to almost the saturated temperature of 4.4 K, while the outlet temperatures were raised to 3.95 K from 3.80 K.

IV. DISCUSSION

We will begin by considering the temperature distribution in the helical coil cooled by subcooled helium. One cooling path of the coil is shown in Fig. 8. Since the longitudinal cooling

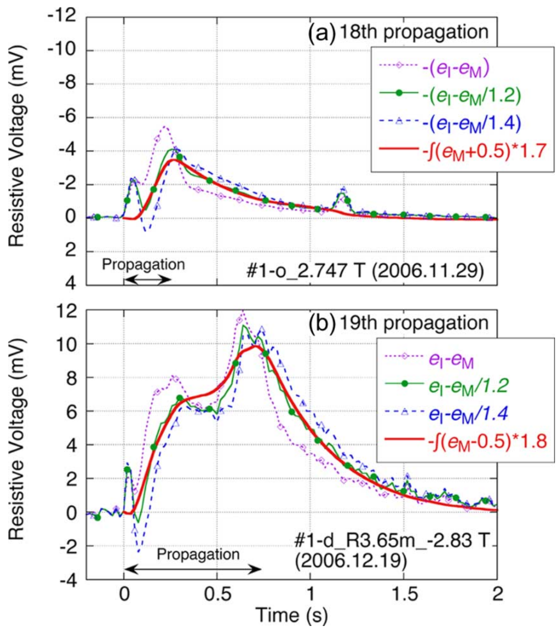

Fig. 7. The estimated normal components for the 18th (a) and 19th (b) propagation of a normal-zone.

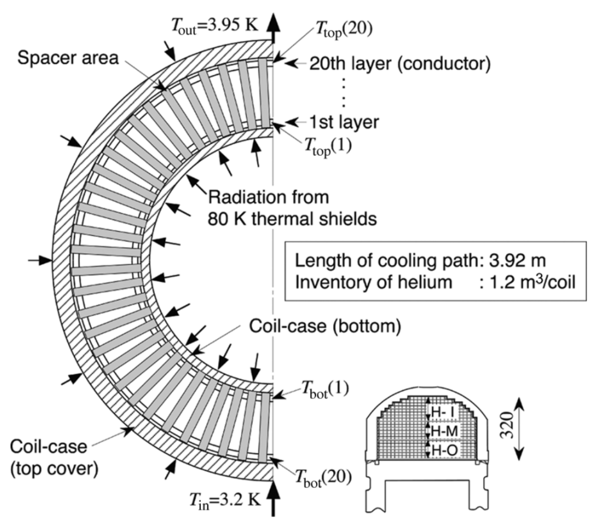

Fig. 8. The schematic drawing of a cooling path of the helical coil. One coil has ten paths.

channels between conductors are blocked with the spacers, additional channels are arranged at the higher side of each layer and both corners of the top cover of the coil-cases. The steady heat input through the cases is uniform along the coil as well as the AC losses in the coils. The increase rate of the helium temperature is the largest at the inlet and become less and less toward the outlet by high thermal conductivity of the conductors. Namely, the conductors are cooled by the helium only at the inlet region and warmed at the other region.

At the bottom of the coil, the supplied helium is heated by the conductors and the coil-cases, and the temperature of helium between the spacers is the higher toward the innermost layers by the natural convection. At the top of the coil, the helium heated by the coil-cases is cooled by the conductors, and the helium temperature can be the higher toward the lower layers that are the innermost layers. Therefore, the conductor temperatures should be the higher at the innermost layers. In addition, the local temperature of helium around them can be higher than the outlet temperature while charging because of the AC losses. Numerical analyses are in progress for quantitative estimation of the temperature distribution.

In order to lower the temperature raised by the AC losses, the excitation method was revised to that the current was held for more than two hours at about 11.0 kA before the excitation to the higher current. This method has attained excitations up to equivalent 11.5 kA without propagation of a normal-zone. The excitation tests to the higher currents are planned with the same method.

V. Summary

In order to improve the cryogenic stability of the LHD helical coils, an additional cooler at 3.0 K was installed. The inlet and outlet temperatures of the coils were successfully lowered to 3.2 K and 3.8 K, respectively, with a mass flow of 50 g/s. In spite of a half charging rate to reduce AC losses, a normal-zone has been induced near the top of the coil at 11.4 kA while the outlet temperatures was raised to 3.95 K by mainly the increased hysteresis losses. The local temperature of the innermost layers near the top is considered to have been raised up to almost the saturated temperature of 4.4 K due to the losses and the natural convection. Therefore, the excitation method has been revised. By holding the current at about 11.0 kA for more than two hours for cool-down, the excitations up to equivalent 11.5 kA have been attained. The excitation tests to the higher currents are planned with the same method.

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