§5. Propagation of A Normal-zone in the LHD Helical Coils Cooled by Subcooled Helium

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Propagation of a normal-zone had been observed 17 times in helical coils of LHD until 2003. 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. Since then, propagation of a normal-zone had been observed eight times, which are the 10th to 17th ones in Table 1. The helical coil is divided into three blocks, H-I, M, and O from the inside. 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 cooling condition will be locally 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 helical coil in 2006. The coil inlet and outlet temperatures have been successfully lowered to 3.2 K and 3.8 K, respectively.[1]

Excitation tests of the helical coils cooled by subcooled helium were carried out while controlling an increase of the outlet temperatures by slow charging rate to reduce AC losses. In spite of that, a normal zone has been induced near the top of No. 8 section of the coil at 11.45 kA in the first higher excitation test. 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. In this cooling cycle, propagation of a normal-zone was observed again at the comparable current in the first excitation after the polarity was changed. The outputs of the pick-up coils for the 19th normal zone are shown in Fig. 1. It was also initiated near the top and propagated to one side. 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 locally, probably at top and bottom, by the AC losses. Figures 2(a) and (b) show resistive components in the balance voltages. The resistive component can be derived by integrating the H-M balance voltage, because the normal-zone propagated in the H-I block with a current shift in the conductor.[2] 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 position of the conductor in which the normal-zone propagated. The value of 1.2 means that the conductor will be the first turn in the fourth layer.

In comparison with the stability tests of a model coil, 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 by the excitation. Therefore, the higher excitation method was changed to that the current was held for more than two hours at about 11.0 kA before the higher excitation. This method has attained the excitation up to equivalent 11.5 kA without a normal zone.

Table 1. 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/ ← / ←	H1-I	#10 bottom
11th	#1-o_γ1.258	11.71/11.57/10.94	H1-I	#10 bottom
12th	#1-o	11.04/ ← / ←	H1-I	#10 bottom
13th	#1-o	11.15/ ← / ←	H1-I	#10 bottom
14th	#1-d	11.30/ ← / ←	H1-I	#10 bottom
15th	#1-c	-11.08/ ← / ←	H2-I	#5 bottom
16th	#1-o	-11.11/ ← / ←	H2-I	#5 bottom
17th	#1-c_R4.0 m	11.00/ ← / ←	H1-I	#10 bottom
18th	#1-o_-2.747 T	-11.45/ ← / ←	H2-I	#8 top
19th	#1-d_R3.65 m	11.75/11.35/11.35	H1-I	#3 top

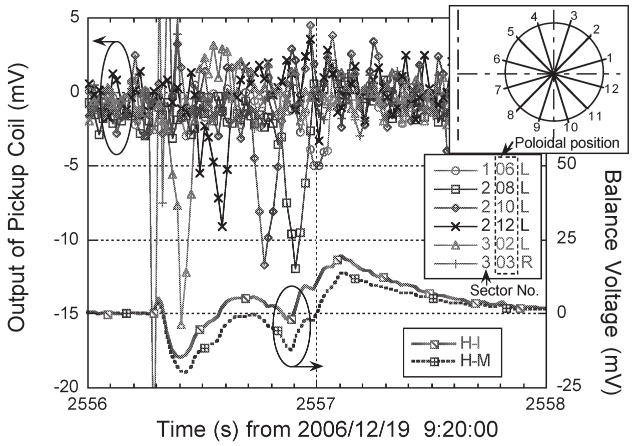

Fig. 1. Balance voltage of the helical coils and output of pickup coils during the 19th propagation of a normal zone.

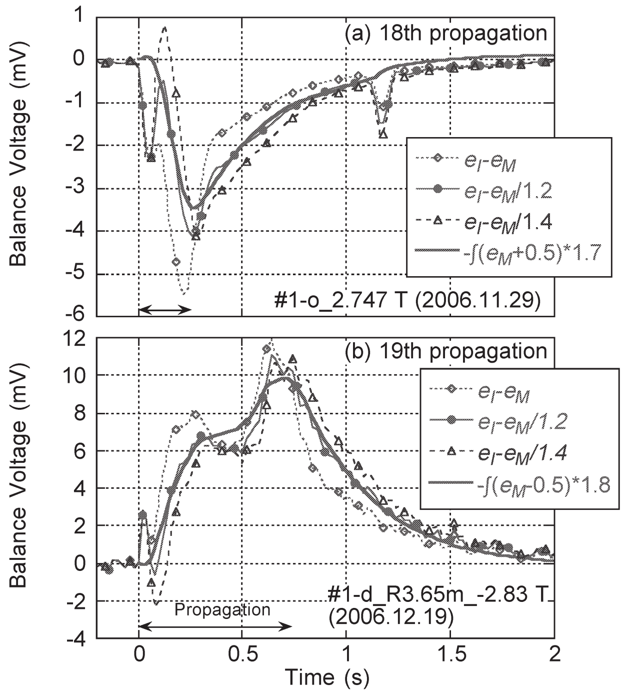

Fig. 2. The estimated normal components for the 18th (a) and 19th (b) propagation of a normal-zone.

Reference

1) Imagawa, S. et al., Nuclear Fusion **47** (2007) 353.

2) Imagawa, S. et al., IEEE Trans. Appl. Supercond. **14** (2004) 1388.