§3. Results of Lowering Temperatures of the LHD Helical Coils by Subcooling System

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The toroidal field of almost 3 T is produced by a pair of pool-cooled helical coils in the Large Helical Device (LHD). When they were cooled with saturated liquid helium at 4.4 K, a normal-zone had been induced several times in their innermost layer at the higher current than 11.0 kA. In order to improve the cryogenic stability by lowering temperatures, an additional cooler with two-stage cold compressors has been installed at the inlet of the coil in 2006.[1] 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. Stable operation of the subcooling system has been established, and the standard operating current can be increased up to 11.4 kA.[2] Furthermore, the operation current has been raised up to average 11.6 kA with the current grading method, in which the current of the innermost block was decreased and those of the other two blocks were increased.

From the results of the stability tests with a model coil, the minimum propagating currents was expected to increase to almost 12.0 kA at 3.5 K, as shown in Fig. 1. A short normal zone, however, was induced at 11.4 kA even with the revised excitation method, in which the current is held at nearly 11.0 kA for more than two hours before the higher excitation to cool-down the temperature rise by ac losses during the excitation. The propagation velocity in the LHD can be estimated from the time delay of the peak voltage of pickup coils that are installed along the helical coils by the pitch of 60 degrees in the poloidal angle. Examples of the estimated velocities are shown in Fig.2. The propagation velocity is faster at the higher magnetic field area. The slowest velocity in the saturated helium at 4.4 K is 6 m/s, which is same as that of the model coil, as shown in Fig. 3. The slowest value is determined by the effect of uncontinuity of cooling condition. In these cases, one third of the conductor surface area is covered by spacers, the length of which is approximately 20 mm.

The normal zone at 11.4 kA under subcooling operation was induced at the bottom of #10 sector, and it propagated to the outer mid plane and stopped there. Its propagation velocity was 6 m/s, which is slower than the slowest value in the model coil in subcooled helium. The reason is not clear yet, but the difference of disturbance should be affected. A tape heater between the conductor and a layer-to-layer insulator was used in the model coil to initiate a normal zone. The length of initial normal zones should not be sufficient in subcooled helium, although the heater power was much enough to produce a normal-zone. Since the actual heating power of the conductor is limited by the thermal resistance of electrical insulator of the tape heater and the contact resistance, it should be less than that of the actual disturbance by the conductor movement. In the helical coil, large conductor movement can induce the higher temperature rise, which enables propagation at the lower current than the model coil.

1) Imagawa, S. et al., Nuclear Fusion **47** (2007) 353.
2) Imagawa, S. et al., IEEE Trans. Appl. Supercond. **18** (2008) 455.

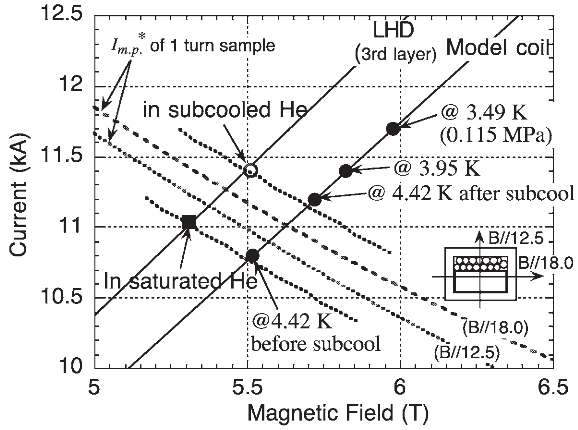

Fig.1. Minimum currents for dynamic propagation of a normal-zone, $I_{(mp)}$*. Normal-zones in the LHD helical coil are estimated to be induced at the third layer.

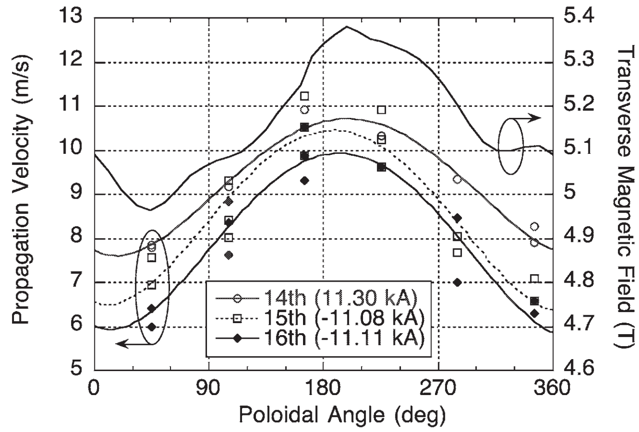

Fig. 2. Propagation velocities of a normal zone in the LHD helical coil and the transverse magnetic field at 11.2 kA at the conductor in which the normal-zone propagated.

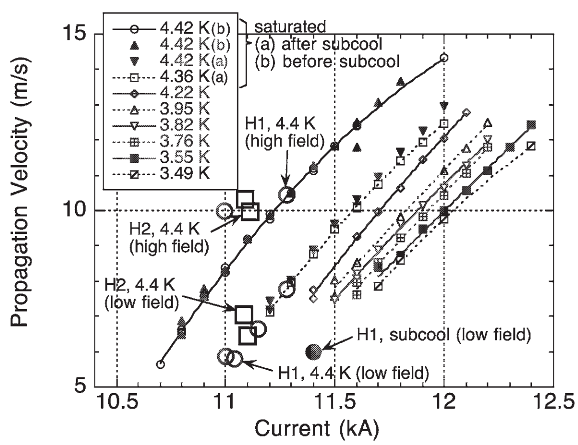

Fig.3. Comparison of propagation velocities in the LHD helical coil and the model coil.