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§3. Effects of Subcool on Lengths of Propagating Normal Zones in the LHD Helical Coils

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One-side propagation of a normal zone has been observed several times in helical coils of the Large Helical Device (LHD). Their currents and magnetic field are shown in Fig. 1. The asymmetric propagation velocity is considered to be caused by electromagnetic interaction of the external magnetic field with the transfer current between the superconducting strands and the pure aluminum stabilizer at the ends of a normal zone. In the 17th campaign of LHD experiments, the 25th propagation of a normal zone was observed under the subcooling operation in which the inlet and outlet helium temperatures are below 3.5 K and 4.0 K, respectively. Its balance voltage is shorter and lower than that of the propagation in saturated helium at 4.4 K.

When a normal-zone propagates in the I-block, the voltage drop due to the resistance of the normal-zone V_R is expressed by

$$V_R = e_I - \frac{\dot{M}_{Ik}}{\dot{M}_{Mk}} e_M = e_I - \frac{B_I I_M}{B_M I_I} e_M \equiv e_I - \frac{e_M}{\alpha} \qquad (1)$$

where e_j and I_j are the balance voltages and the currents of j block, respectively[1]. B_j is the magnetic field density by j-block at the conductor where the normal zone propagates. Figure 2 shows the resistive components derived from the difference between the balance voltages in H-I block and H-M block for the 17th, 23rd, and 25th propagations. The parameter α corresponds to the position where the normal-zone propagates, and α=0.7 means that the normal zone propagated in the first layer of the H-I, where the field is the highest.

The voltage drop during propagation of a normal zone was measured in the model coil using voltage taps. It can be fitted by exponential functions using the duration of propagation, t_r, as shown in Fig. 3, where the recovery starts before the current deeply diffuses into the aluminum. The resistive voltages calculated by the fitting equation with t_r=0.08 s at the propagation velocity of 6 m/s for the 17th propagation and t_r=0.02, 0.03, and 0.04 s at 7 m/s for the 25th propagation are shown in Fig. 4. The lengths of propagating normal zones at the minimum propagation currents are obviously shorter in subcooled helium than in saturated helium in spite of the higher operating current. The shorter length of the normal zone is caused by the quicker starting of recovery. In subcooled helium, the recovery starts within 0.02-0.03 s after the normal transition. It is shorter than the time constant of current diffusion into the pure aluminum stabilizer. It is considered that a normal zone in subcooled helium at the current close to the minimum propagation current propagates without the transition from the nucleate boiling to film boiling.

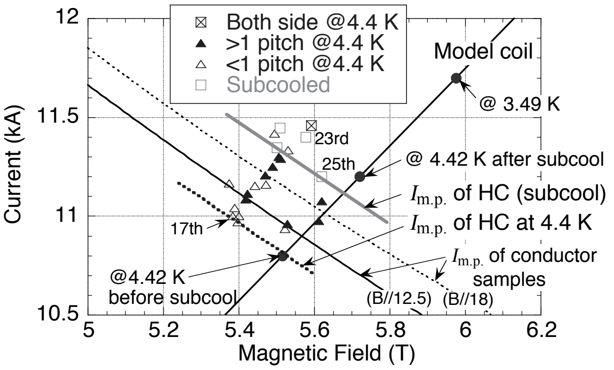

Fig. 1. Minimum propagating current, $I_{m.p.}$, of LHD helical coil. The magnetic fields of LHD are at the bottom.

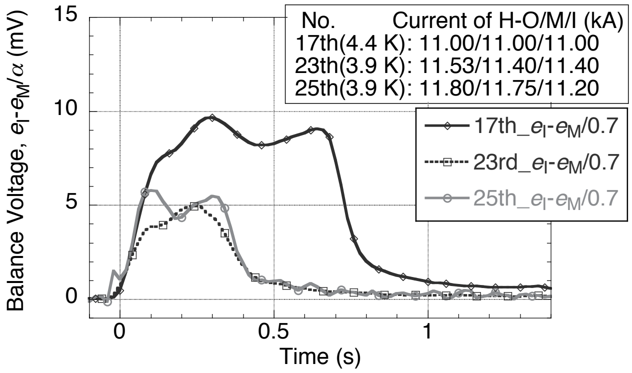

Fig. 2. The resistive voltage at 17th, 23rd, and 25th propagation of normal zones in the LHD helical coil.

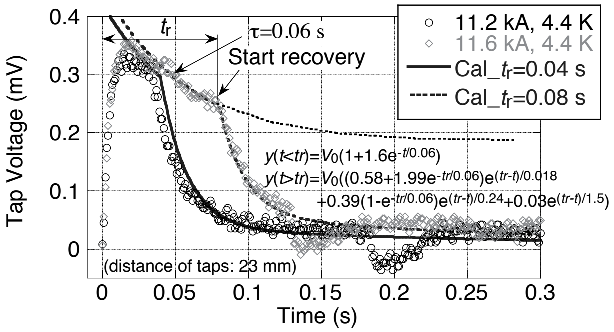

Fig. 3. Output of voltage taps of the helical coil conductor during one-side propagation of a normal zone in the HC model coil.

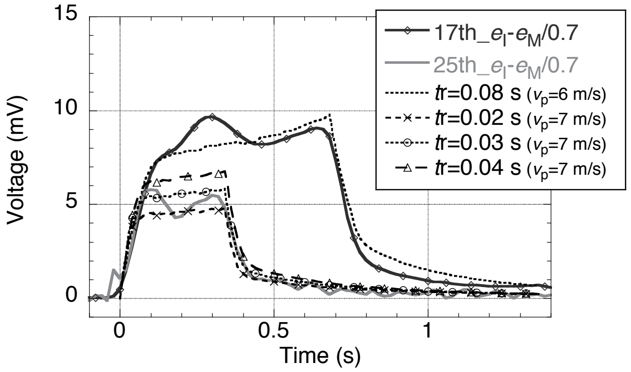

Fig. 4. Calculated resistive voltage at the 17th and 25th propagations. The stopping time of the propagation is set at 0.68 and 0.34 s, respectively.

1) Imagawa, S. et al.: IEEE Trans. Appl. Supercond., **23** (2013) 4700904.