§2. Reconsideration of Evaluation of Balance Voltages during Normal Zone Propagation in the LHD Helical Coils

Imagawa, S.

One-side propagation and recovery of normal zones were observed 24 times in a pair of LHD helical coils, which are named H1 and H2. Each the coil is divided into three blocks, which are named H-I, H-M, and H-O from the inside. When a normal zone propagates, balance voltages between H1 and H2 are induced in all the blocks because of a shift of current center from the superconducting wires to a pure aluminum stabilizer at the normal zone. The cross-sectional position of the conductor in which the normal zone propagates can be estimated from the difference among the balance voltages of the blocks. In the previous study, the conductor positions were estimated at the first or last turn in the third and fourth layers of the H-I under the assumption that the resistive voltage is in proportion to the normal zone length.[1] This assumption is not precise because the transient high resistance is induced by slow current diffusion into the stabilizer. Considering the transient resistance of the normal zone, the estimation method is reconsidered.

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. B_j is the magnetic field density by j -block at the conductor where the normal zone propagates. The ratios of magnetic field at each turn by M-block to that by I-block are shown in Table I.

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. 1, where the recovery starts before the current deeply diffuses into the aluminum. The resistive voltages calculated by the fitting equation with t_r=0.10 and 0.12 s are shown by lines in Fig. 2, in which the resistive voltages evaluated by (1) are also shown for α=0.7. 0.8 and 0.9. Since the profile at α=0.7 is in good agreement with the calculation, the normal zone is considered to have propagated in the first layer of the H-I, where the field is the highest. This result is in agreement with the evaluation of measured data with pickup coils along the helical coils.[2]

Resistive components of all normal zones, except for the 4th that is both-side propagation, are investigated by the same method. The result for the propagation within one pitch is shown in Fig. 3. Five normal-zones were initiated in the second layer, and the others were in the first layer.

1) Imagawa S. et al., *IEEE Trans. Appl. Supercond.*, vol. 13 (2003) 1484.
2) Imagawa S. et al., *IEEE Trans. Appl. Supercond.*, vol. 21 (2011) 2316.

Table 1 Max. and Min. ratio of the magnetic field in the overturning direction by M-block to that of by I-block.

Layer	T4	T5	T6	T7	T8	T9	T10	T11
L1	Max.					0.69	0.68	0.68
	Min.					0.67	0.67	0.67
L2				0.79	0.81	0.87	0.89	0.90
				0.78	0.80	0.86	0.89	0.89
L3		0.94	0.96	1.09	1.17	1.25	1.31	1.34
		0.93	0.95	1.06	1.13	1.19	1.24	1.26
L4	1.24	1.45	1.60	1.81	2.02	2.22	2.37	2.47
	1.19	1.35	1.47	1.63	1.77	1.90	2.01	2.07

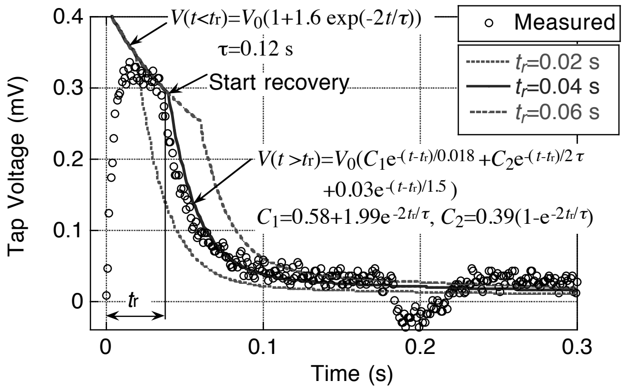

Fig. 1. Voltage drops of the LHD-HC conductor during propagation and recovery of a normal zone at 11.2 kA, 4.4 K. The distance of voltage taps is 23 mm.

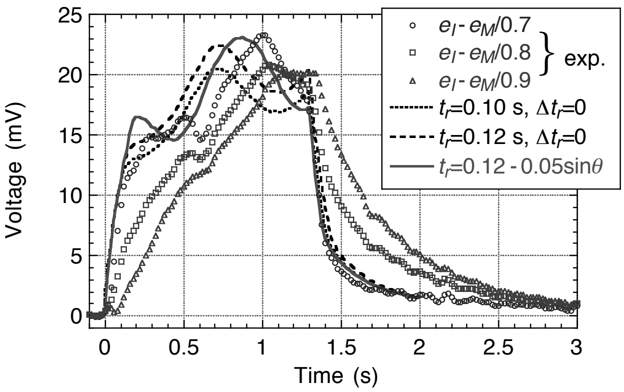

Fig. 2. Calculated normal component of voltage during the 14th propagation of a normal zone in the LHD helical coil.

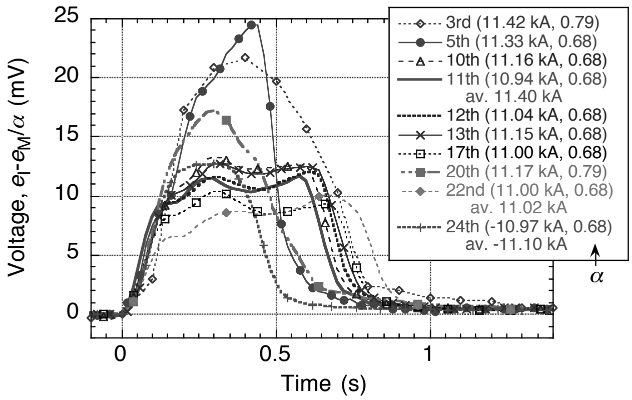

Fig. 3. Resistive components of normal zones that stopped within one pitch of the helical coil. The 3rd and 20th normal zones are considered to have propagated in the 2nd layer, and the others are in the 1st layer.