§3. Analysis of Propagating Short Normal Zones in the LHD Helical Coils

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Short normal zones propagating to one-side were observed in the helical coils and in a model coil. The shorter length of the normal zone is caused by the quicker starting of recovery, that is the shorter duration of transition to normal state, t_r. Figure 1 shows t_r in the model coil for different helium temperatures[1)]. The minimum current for each temperature corresponds to the minimum propagating current. The t_r at a fixed temperature is longer at high currents, and the t_r at the minimum propagating current is shortened as the temperature is lowered. In order to simulate these short normal zones, a calculation model is proposed[2)]. Since thermal conductivity in copper and aluminum is sufficiently high, the conductor is divided into 5 elements, as shown in Fig. 2, which are half of the copper sheath on the strands side (Cu1), NbTi/Cu strands and PbSn solder (SC), the CuNi layer between the strands and the aluminum stabilizer (CuNi), the aluminum stabilizer and the rest of the CuNi layer (Al), and half of the copper sheath on the stabilizer side (Cu2). The size and conditions of the analysis model is shown in Fig. 3. The pitch length of spacers between turns is 54 mm with the wetted surface of 67%, meaning that the cooled area is 36 mm. The heat balance of the elements is solved with a finite differential method with the time step of 0.2 μs. The transient heat generation during current diffusion into a stabilizer is considered, and the heat transfer in liquid helium is fitted from the experimental data with a conductor sample at vertical position.

The suitable parameters for K_{12} to K_{45} and heat transfer efficiency, *HF* were surveyed to simulate both the minimum propagating currents with an error less than 0.1 kA and the propagation velocities with an error less than 10%. A suitable set of K_{12} to K_{45} depends on *HF*. The dependence of propagation velocity on the current is better fitted with fairly small K_{23}, which suggests insufficient contact between the strands and the CuNi layer. Although short propagating normal zones with t_r~0.02 s can not be simulated yet, a representative result for quick recovery with t_r~0.04 s is shown in Fig. 4. The highest temperature of Cu1 except for the heated region is lower than 7.3 K that is in the transition region from nucleate boiling to film boiling. In the case the reached temperature in the normal zone is higher, the recovery starts more slowly. The main cause for the quick recovery is low reached temperature in the normal zone. Since the reached temperature of Cu1 at t_r~0.02 s must be lower than that at t_r~0.04 s, such a short normal zone is considered to propagate without full transition to film boiling. In other words, a normal zone can propagate under the good heat transfer due to the temperature rise in the oxidized surface.

1) Imagawa, S. et al.: IEEE Trans. Appl. Supercond., **23** (2013) 4700904.
2) Imagawa, S., Proc. 24th ICEC/ICMC (2013) 591-594.

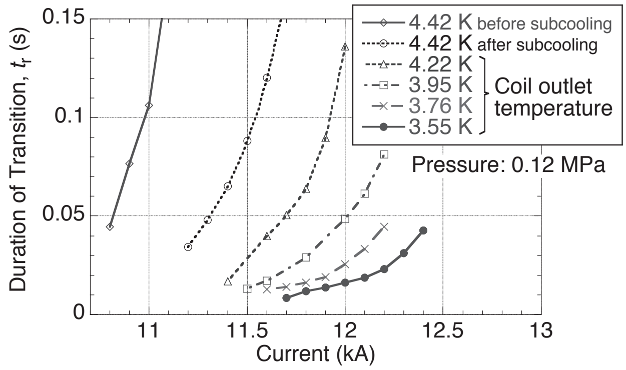

Fig. 1. Durations of transition to normal state in the model coil. They are averaged values for six voltage taps in 0.32 to 1.13 m from the heater.

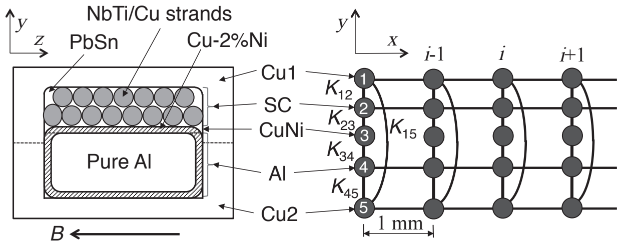

Fig. 2. Cross-section of a helical coil conductor and the analysis model, where K_{12}, K_{23}, K_{34}, K_{45}, and K_{15} are thermal conductances between the elements. The thermal conduction of CuNi in the longitudinal direction is ignored, because the thermal conductivity of CuNi is low enough.

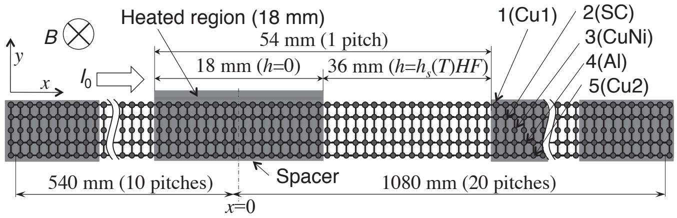

Fig. 3. The size and conditions of the analysis model. The external heat is input into Cu1. *h* is the heat transfer in the calculation, and $h_s(T)$ is the experimental value with a conducotr sample. *HF* is the efficiency of heat transfer.

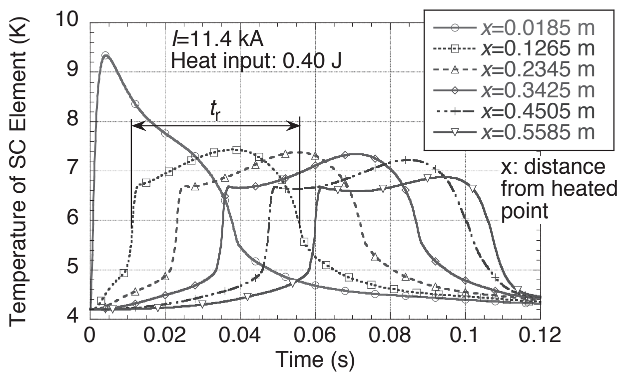

Fig. 4. Calculated temperatures of one-side propagation of a normal zone at 11.4 kA with HF=0.95, $K_{12}/K_{23}/K_{34}/K_{45}$ =100/20/100/50 W/m/K, the initial helium temperature of 4.2 K and the saturated temperature of 4.4 K. The temperature at x=0.0185 m is affected by the heater.