Numerical analysis on effect of Kapitza conductance on stability of LHD conductor cooled by He II

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Abstract. An analytical code to simulate the dynamic one-side propagation of a normal zone observed in the LHD conductor was developed. The dynamic one-side propagation phenomenon is the one in which a short normal zone initiated by a thermal disturbance dynamically propagates only to one side along the conductor and shrinks after a few seconds. This code was based on the two-dimensional heat balance equation, current diffusion ones, Hall effect and database on the cooling properties of He II. Using the proposed code, numerical analyses were performed on two LHD conductors with different surface conditions (oxidized and polished). The asymmetrical propagation phenomenon was successfully simulated. The analytical results showed that the stability of the LHD conductor becomes better with making Kapitza conductance large. One of the main factors that govern the stability of the LHD conductor cooled by He II is Kapitza conductance.

1. Introduction
The Large Helical Device (LHD) is a Heliotron-type fusion experimental device, which consists of a pair of superconducting helical coils and three pairs of superconducting poloidal coils. The helical coils are now pool-cooled with saturated liquid He I (4.4 K) in the Phase I program [1]. During recent excitation tests of the LHD, a normal transition occurred at the innermost layer of the helical coils, and a coil quench followed [2]. This event occurred at the current and magnetic field slightly lower than the designed operation point. In order to achieve a higher magnetic field, the change of the cooling mode to subcooled He I cooling is planned, and the liquid helium temperature would be lowered to 1.8 K in the Phase II program.

Previously, we carried out the stability tests for a small LHD conductor coil [3], [4], and the advantage of He II over He I cooling was clarified. However, the dynamic one-side propagation of a normal zone was observed in a wide current range below the quench current with lowering coolant temperature. The dynamic one-side propagation phenomenon is the one in which a short normal zone initiated by a thermal disturbance propagates only to one side along the conductor and disappears in a lower magnetic field area. This phenomenon may lower the stability limit of the LHD helical coils when the higher excitation of the LHD magnet is realized by lowering the coolant temperature.

The delay of the current diffusion in the aluminum stabilizer is the most serious cause that makes the transient stability of the LHD conductor worse than the steady-state one. On the other hand, the surface of the LHD conductor is chemically oxidized, and the Kapitza conductance on an oxidized copper surface is known to be quite smaller than that on a polished copper surface [5]. Kapitza
conductance will deeply affect the stability of the LHD conductor immersed in He II. In this paper, the effect of Kapitza conductance on the stability of the LHD conductor cooled by He II was studied numerically by using an analytical code developed recently [6].

2. Analytical model and method

The cross-sectional view of the LHD conductor is shown in Figure 1 (a). The LHD conductor is a composite superconductor, which consists of a NbTi/Cu Rutherford cable, a pure aluminum stabilizer and a copper sheath, and a Cu-oxide layer covers the outer surface of it [7]. In this paper, numerical analyses are performed on two LHD conductors with an oxidized and polished copper surface.

Figure 1 (b) shows the two-dimensional analytical model. The transport current $I$ flows along the $z$-axis, and the external magnetic field $B_0$ is applied in the positive $x$-direction. The basic equations that govern the current diffusion in the conductor are

$$\frac{\partial J}{\partial t} = \nabla^2 E - \nabla (\nabla \cdot E)$$  \hspace{1cm} (1)

$$E = \rho(B)J - R_H J \times B_0$$  \hspace{1cm} (2)

where, $J$ is the current density, $\rho$ is the electrical resistivity, $\mu_0$ is the magnetic permeability and $R_H$ is the Hall coefficient.

The governing heat balance equation is given by

$$C(B,T) \frac{\partial T}{\partial t} = \nabla \cdot (k(B,T) \nabla T) + Q_j + Q_h$$  \hspace{1cm} (3)

where, $C$ is the heat capacity, $k$ is the thermal conductivity, $Q_j$ is the Joule heat density and $Q_h$ is the energy density of a thermal disturbance. The thermal disturbance is assumed to be uniformly applied on the 10 mm-length heater part shown in Figure 1 (b).

The equations (1) - (3) can be solved by the finite difference method. The mesh size is 0.5 mm ($z$) × 0.22 mm ($y$), and the time step is $1.0 \times 10^{-7}$ s. At $t = 0$, the transport current $I$ flows only through the SC part uniformly, and the whole conductor temperature is equal to the bulk temperature $T_b$. Under these conditions, the pulsive heat input is applied to the conductor for 1 ms. On the boundaries between different materials, $J_n$ and $E_t$ must be continuous. At the exterior boundaries, $J_n = 0$, where $J_n$ is the normal component of the current density and $E_t$ is the tangential component of the electric field.

The temperatures at the longitudinal ends of the conductor are set to be constant as $T_b$.

The non-boiling heat transfer between the conductor surface and He II is controlled by a phenomenon called Kapitza conductance. On the upper and lower surfaces, the effective cooling heat flux $q_{c,eff}$ equation in the Kapitza conductance regime is used.

$$q_{c,eff} = \alpha \times q_c = \alpha \times \beta \times (T_{cu} - T_b)$$  \hspace{1cm} (4)

Where, $q_c$ is the heat flux equation for the Kapitza conductance regime given by Iwamoto [5] and $T_{cu}$ is the copper surface temperature. $n$ and $\beta$ are the fitting parameters, and $n = 2.861$ and $\beta = 202.5$.

Figure 1. (a) Cross-sectional view of LHD conductor. (b) 2-D analytical model along the conductor.
W/m²K\(^n\) for the oxidized surface, \(n = 3.001\) and \(\beta = 701.6\) W/m²K\(^n\) for the polished surface. \(\alpha\) is the dimensionless correction coefficient, which is determined by taking the cooling from the side surfaces of the LHD conductor into account (see Figure 1 (a)), and \(\alpha = (18.00 + 4.82 \times 2) / 18.00 = 1.54\) for the lower surface and \(\alpha = (18.00 + 7.68 \times 2) / 18.00 = 1.85\) for the upper surface. The conductor surface is thermally insulated in parts with the interval of 55 mm as shown in Figure 1 (b), and the exposure of the conductor surface is set up to 67% for simulating the actual LHD helical coils. The numerical analyses are performed for the magnetic flux densities \(B_0\) from 4 to 7 T at the bulk liquid helium temperature \(T_b\) of 2.0 K.

3. Analytical Results

3.1. Dynamic normal zone propagation

Propagation characteristics of the initiated normal zone were classified into the following three groups. Figure 2 shows the typical Joule heat distributions belonging to the second and third groups at \(t = 10\) ms for the polished conductor. The analytical conditions are \(B_0 = 6\) T, \(Q_h = 2.27 \times 10^9\) W/m\(^3\).

(Group I) A normal zone is initiated only around the heater in response to the heat input. After shutting off the heat input, the conductor recovers to the superconducting state.

(Group II) As shown in Figure 2 (a), at \(I = 18\) kA, an initiated normal zone propagates only to one side along the conductor, and a normal zone with a finite size separates from that of the heater part. It propagates through the test part, and reaches the rightmost thermal insulation. This phenomenon is called “dynamic one-side propagation”. Such an asymmetrical propagation is caused by circulating Hall currents, which flow between the lower copper sheath and superconducting strand (SC), and between the aluminum stabilizer and SC part across the CuNi clad. They make the asymmetrical Joule heat distribution in the SC part, which results in the asymmetrical normal zone propagation. The details are given in [6].

(Group III) As shown in Figure 2 (b), at \(I = 19\) kA, an initiated normal zone propagates to both sides along the conductor. Two normal zones, which are separated from the both ends of the initiated normal zone respectively, propagate through the test part, and reach the rightmost and leftmost thermal insulations respectively.

3.2. Stability of oxidized and polished LHD conductor

Figure 3 shows the analytical results for the oxidized and polished conductor at \(T_e = 2.0\) K. The triangular, double circular and square dots indicate the analytical results belonging to the three groups respectively. Now the first minimum propagation current \(I_{p1}\) (dashed line) is defined as the current above which a normal zone will propagate only to one side along the conductor, and the second

![Figure 2](image)

**Figure 2.** Joule heat distributions along the polished conductor at 10 ms from the heat input. (a) \(I = 18\) kA and (b) \(I = 19\) kA.
minimum propagation current \( I_{p2} \) (solid line) is defined as the current above which a normal zone will propagate to both sides along the conductor.

Both \( I_{p1} \) and \( I_{p2} \) for the polished conductor at a certain magnetic field are significantly large compared with those for the oxidized one as shown in Figure 3. For instance, at the magnetic flux density of 5 T, \( I_{p1} \) and \( I_{p2} \) for the polished conductor are 1.3 times those for the oxidized one. This is due to the difference in the Kapitza conductance. The difference between the heat flux \( q_c \) on the polished surface and that on the oxidized one increases with increasing copper surface temperature \( T_{Cu} \). The heat flux on the polished surface is 4.38 times that on the oxidized one at the copper surface temperature of 5 K. Such a higher heat flux on the polished surface in the Kapitza conductance regime makes the polished conductor considerably stable than the oxidized one. The Kapitza conductance deeply affects the stability of the LHD conductor, and higher Kapitza conductance on the LHD conductor surface produces higher stability of the conductor in He II.

4. Conclusions

Propagation characteristics of the initiated normal zone are classified into the three groups: (I) a normal zone is initiated only around the heater in a moment and the conductor finally recovers to the superconducting state, (II) an initiated normal zone propagates only to one side along the conductor, (III) an initiated normal zone propagates to both sides along the conductor.

The polished LHD conductor is more stable than the oxidized one. Kapitza conductance deeply affects the stability of the LHD conductor immersed in He II, and higher Kapitza conductance on the LHD conductor surface produces higher stability of the conductor.

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Figure 3. Comparison of analytical results for oxidized conductor with those for polished one as a function of magnetic field.