LESSONS FROM DESIGN AND MANUFACTURE OF U.S. LCT COILS

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STABILITY TEST RESULT OF THE JAPANESE TEST COIL FOR THE LARGE COIL TASK AT THE DOMESTIC TEST


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Résumé - La conception de la bobine japonaise LCT, était basée au départ sur le critère de stabilité dit de "récupération avec une extrémité froide". Néanmoins, par suite des développements apportés sur la surface de refroidissement du conducteur, la bobine définitive peut être considérée comme remplissant les conditions de stabilité inconditionnelles, supérieure à celle de l'extrémité froide. Cette stabilité est confirmée par les résultats des tests et une analyse détaillée. La marge de courant dans les conditions nominales de fonctionnement est estimée à environ 22 %.

Abstract - The designing work of the Japanese LCT coil was begun based on the cold end recovery criterion. But, as the result of research and development work on the conductor's cooling surface, the completed coil was estimated to be in the unconditional recovery region more stable than the cold end one. This is verified in this paper by the results of the domestic test and the detailed analysis. The estimated current margin at the nominal operating condition is about 22%.

Japan Atomic Energy Research Institute carried out the domestic test of the Japanese LCT coil and showed that the coil satisfied its all design criteria that could be confirmed by the single coil test/1/. The stability criterion for the LCT coils specified by Oak Ridge National Laboratory was "to recover fully superconducting state following the occurrence of a half turn length normalcy". In case of the Japanese coil, the conditions for this criterion are the transport current of 10.22 kA, the average current density in winding of 26.6 A/mm², the magnetic field of 8 T and the pool cooling. To get high stability, low ohmic heat generation and high cooling capacity are desired for the conductor. The former depends upon the quantity and the electrical resistivity of the substrate. In case of the Japanese LCT conductor, they were almost determined by the mechanical requirement on the conductor and by the properties of Cu, and, the cooling capacity over 0.7 W/cm² was required for the conductor's cooling surface. After the study of many kinds of surfaces on their heat transfer characteristics/2/, we developed the oxidized roughened surface/3/ whose equal area heat flux is sufficiently high to stabilize the Japanese LCT coil, and, the structure of the conductor was determined as shown in Fig.1 and Table 1. The cooling capacity of the developed surface is very high, so, it was preanalyzed that the coil was in more stable region than the cold end recovery one.

In this paper, we describe the method and results of the analysis at first, and present the results of the domestic test.

Table 1. Major parameters of the Japanese LCT conductor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>8T-conductor</th>
<th>5T-conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall dimensions</td>
<td>12.6 x 26.8</td>
<td>12.6 x 21.3 mm</td>
</tr>
<tr>
<td>Cu/Superconductor ratio</td>
<td>7.28</td>
<td>7.41</td>
</tr>
<tr>
<td>Effective Cu area</td>
<td>227</td>
<td>196          mm²</td>
</tr>
<tr>
<td>Available Cooling Surface</td>
<td>3.47</td>
<td>2.70         cm²/cm</td>
</tr>
<tr>
<td>Rated Current</td>
<td>10.22</td>
<td>10.22        kA</td>
</tr>
<tr>
<td>Current Density (Conductor)</td>
<td>30.3</td>
<td>38.1         A/mm²</td>
</tr>
<tr>
<td>(Winding)</td>
<td>24.2</td>
<td>30.3         A/mm²</td>
</tr>
</tbody>
</table>

Fig.1 The cross-section of the 8T-conductor.
I - STABILITY ANALYSIS

There is very simple criterion/4/ to design a stable coil, but when the stability of a completed coil is tested, a detail analysis which simulates well the condition of the coil must be done in order to evaluate the obtained data correctly. This is particularly necessary in case that the change of the condition along the conductor is strong like the LCT coil. To analyze the stability of the Japanese LCT coil, we solved numerically one dimensional heat flow equation as follows;

\[ \rho \cdot C(T) \frac{dT}{dt} = \frac{2}{\lambda(T)} \frac{dT}{dx} + Q_j(T,x) + Q_d(x,t) - Q_h(T,x) - Q_n(T) \]

where t is time, x is distance along conductor, T, \( \rho \), C and \( \lambda \) are temperature, density, specific heat and thermal conductivity of the conductor respectively. \( Q_j \) is the ohmically generated heat, \( Q_d \) is the disturbance heat, \( Q_h \) is the heat transferred to the liquid helium and \( Q_n \) is the heat conducted to the neighbouring turns.

In the experiment, the disturbance heat is poured by the heater into the conductor, so, in the present analysis, the specific heat of the heater and the thermal resistance between the heater and the conductor were considered. In the test zone, by the decrease of the substrate due to the installation of the heater, the stability limit is estimated to be 12.4 kA - 8 T, while that of the conductor with no heaters is calculated to be 12.7 kA - 8 T/3/.

In case of the Japanese LCT coil, the cooling channel made by the spacers between pancakes changes its orientation along the conductor. According to this change, the cooling characteristics of the conductor's cooling surface change along the conductor. Fig.2 shows the cooling curves measured at the model test and the heat generation curves. The best cooling curve appears at the top and the bottom parts of the coil, and, the conductors in the vertical orientation have the worst one. Even the ohmic generation heat flux at 10.22 kA - 8 T is lower than the minimum film boiling heat flux of the worst cooling curve, that is, the coil is in unconditional recovery region everywhere.

The map of the stability factor along the conductor of the central pancake's innermost turn calculated from the cooling characteristics and the magnetic field is shown in Fig.3. The highest value, the lowest stability, appears at the node 330 at the single coil test and at the node 370 at the six coil test where the magnetic field is the strongest in each case. The dent between nodes 100 and 300 is due to the good cooling characteristics.

Fig.4 shows the calculated temperature profiles on the condition that the coil is in
single 100% charged state (10.22 kA - 6.4 T) and the 0.75 m long test zone is heated. Because of the thermal resistance between the heater and the conductor, it takes rather long time to recover perfectly. The temperature rises faster and remains later where the degree of stability is lower. This result shows that the recovery which looks like the cold end one can be seen even in the unconditional recovery region due to the difference of the stability degree along the conductor.

II - TEST PROCEDURE AND RESULTS

In the Japanese LCT coil, there are 16 half turn test zones where heaters, high speed carbon thin film temperature sensors and voltage taps are installed on the conductor. To insulate from the conductor electrically, there are rather thick insulators around heaters which play as the thermal barrier simultaneously. This barrier dulls the heat pulse which is input to the conductor from the heater. So it was impossible to examine about the transient stability and we took the method to observe the normalcy created on the conductor by the sufficient heat.

The heating power was determined to raise the temperature of the conductor a little above the critical value of the superconductor for each heater at the coil current of zero and was fixed during the stability test. Typical heating powers are 350 J/m - 0.2 sec for heating less than a half turn and 470 J/m - 0.4 sec for a half turn heating.

The stability test was carried out from the low charged state and the short length heating up to a half turn length heating at the 100% charged state (10.22 kA, 6.4 T, 106 MJ). The total number of heating was 207 and all the data of voltage and temperature were taken in the PDP 11/70 data acquisition system. Any unstable behavior could not be seen in the coil during the test and all normalcies created by heaters disappeared spontaneously and perfectly.

Fig.5 shows the voltage and the temperature profiles after heating a half turn length test zone including the strongest magnetic field point at the 100% charged state. The heating power was 2.3 kJ - 0.4 sec which corresponds to 1.7 J/cm³ per unit volume of the conductor. The temperature of the conductor began to rise gradually just after the start of the heating, and, about 0.2 second later, they stood up suddenly which was thought to be the transition from the nucleate boiling to the film boiling. The maximum temperature appeared on the conductor was about 20 K. About the same time with the standing up of the temperature, the voltages appeared. The ohmically generated heat in the conductor calculated from the transport current and the appeared voltage was about 920 W (1.1 J/cm³). The created normalcy began to disappear from the center of the heated zone where the degree of stability was estimated to be the highest. Within 2 seconds after the start of heating, the normalcy died out in course of time perfectly and the coil was proved to be stable against a half turn length normalcy at the 100% charged state.

III - VERIFICATION OF THE UNCONDITIONAL RECOVERY

The type of the recovery seen at the domestic test is the unconditional one. This is verified by Figs.6 and 7.

The life time of the normalcy depends on its length.
in case of the cold end recovery. But this dependency could not be seen at the domestic test as shown in Fig.6.

Fig.7 shows the measured voltage profile after heating the test zone between VH27-28 at the 100% charged state with the calculated one. The calculation was based on the assumption that the coil is in unconditional recovery region but has the distribution of the stability degree as described formerly. The two curves agree very well, so the assumption is proved to be correct.

From these facts, we can say that the coil was in unconditional recovery region at the domestic test.

IV - ESTIMATION OF STABILITY LIMIT
The voltage shrink velocity shown in Fig.8 arises due to the difference of the degree of stability along the conductor and is different from the normal front velocity defined in the cold end recovery region. But the stability limit can be estimated by this voltage shrink velocity because it also depends on the stability. The estimated stability limit from Fig.8 is about 123% which means the transport current of 12.6 kA and the magnetic field of 7.9 T. This value is in good agreement with the calculated one (12.4 kA - 8.0 T). Therefore, the Japanese LCT coil is estimated to be stable at the normal operating condition at the six coil test (10.22 kA - 8.0 T) with the current margin of 22%.

V - CONCLUSIONS
Stability test was carried out on the Japanese LCT coil at the domestic test. A half turn normalcy created by the heater at the 100% charged state (10.22 kA, 6.4 T, 106 MJ) disappeared spontaneously and the coil was proved to be stable. The test results were in good agreement with the calculated one. Results are summarized as follows;

1) The coil was in the unconditional recovery region at the domestic test as was preliminary estimated and is expected to be in the same region at the normal operating condition at the six coil test (10.22 kA - 8.0 T).
2) The stability limit of the coil is estimated to be about 12.5 kA - 8 T both experimentally and analytically which corresponds to the current margin of about 22% at the normal operating condition at the six coil test.

These good results on stability are mainly due to the developed oxidized roughened cooling surface. And owing to plenty of data from the tests carried out before and during manufacture of the coil, the accuracy of the analysis was much raised. From these results, much larger pool-cooled stable coils can be designed as far as the stability concerned.

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REFERENCES