Thermal Analysis of Cryocooler-Cooled Bi2223 Pulsed Coil

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Abstract. We fabricated a cryocooler-cooled Bi2223 superconducting pulsed coil and experimentally studied thermal runaway in dc or ac operation. We carried out numerical simulation of thermal properties of the coil in order to explain thermal runaway of the coil. Firstly, we analyzed the total heat generation of flux-flow loss and ac loss inside the winding from the experimental results of the external field losses and the $E-J$ characteristics for the Bi2223 strands. Secondly, we numerically simulated the thermal properties by using 2-dimensional heat conduction equation with axial symmetry. The numerical simulation shows the relation between the initiation of thermal runaway and the temperature distribution with highly concentrated heat source in the winding. We have a semi-quantitative agreement between the numerical results and the experimental ones for the condition of the thermal runaway.

1. Introduction
We designed and fabricated a cryocooler-cooled Bi2223 superconducting pulsed coil [1] in order to study the thermal stability of the cryocooler-cooled system. One of the most important factors for the thermal stability is thermal runaway [2]. We measured the thermal runaway current in dc or ac operation [3]. In this study, we observed the relation between thermal runaway and the operational condition of transport current of 3 Hz and coil temperature. The experimental results gives a map of stability, including the conditions of stable operation and the initiation of thermal runaway, for the transport current and the coil temperature. We also calculated the distribution of flux-flow loss and ac loss in the winding from experimental results of the external field losses and the $E-J$ characteristics of the Bi2223 strands, and carried out numerical simulation of the thermal properties to explain the map of stability.

2. Experimental
2.1. Coil system
The pulsed coil was wound with a Bi2223 4-strand parallel conductor [1]. The strands were transposed for the purpose of uniform current distribution and low ac loss. The coil was cooled by a single stage GM-type cryocooler. Laminated copper plates connected a cryocooler head and both coil flanges, and aluminum nitride (AlN) plates were arranged among layers as heat drains to suppress a temperature rise. In addition, to reduce the thermal contact resistance between the superconducting wires and the AlN plates, the epoxy resin with high thermal conductivity, which contains MgO powders, was fully spread on them during the winding process.

2.2. Thermal runaway
In our previous study, we have already measured the temperature distribution in ac operation of 0.5 to 5 Hz with sinusoidal waveform by setting 9 thermocouples inside the winding [3]. For example, the temporal variations of the averaged coil temperature from the initial level of 50 K in the ac operation of 3 Hz with the amplitude of 130 and 160 A are shown in figure 1. Here, we shall define turning temperature as the starting temperature to the thermal runaway. In the case of the initial temperature of 160 A, the coil temperature first increases gradually and the coil falls into the thermal runaway around the turning temperature of 66 K. On the other hand, in the case of the initial temperature of 130 A, the coil temperature initially increases gradually during the first 100 minutes, and it finally approaches to the balanced temperature of 55 K.

The thermal runaway currents for the initial and turning temperatures are shown by circles and squares, respectively in figure 2. Figure 2 shows also the balanced temperature. In this way, figure 2 gives a map of stability, including the condition of stable operation and the initiation of thermal runaway, for the transport current and the coil temperature. The thermal runaway currents for the initial temperature or the turning temperature are decreasing monotonically with increasing temperature. However, in a low temperature region, the thermal runaway current for the initial temperature is almost constant (160 A). If a coil temperature and a current value were in the region of A, the coil temperature first increases gradually, and the coil falls into thermal runaway beyond the turning temperature shown in figure 2. On the other hand, if a coil temperature and a current value were in the region of B1 or B2, the coil temperature approaches to the balanced temperature shown in figure 2.

**Figure 1.** Average coil temperature variations from initial coil temperature of 30 K in sinusoidal operation of 3 Hz with the amplitude of 130 and 160 A.

**Figure 2.** Thermal runaway currents for initial temperatures or turning temperatures in sinusoidal operation of 3 Hz and balanced temperature for coil temperatures is also indicated.
2.3. Discussion
We measured heat generation inside the winding by usual electrical method [3] in ac operation of 3 Hz with the current amplitude of 60, 85, 95, 140, 150, or 160 A. The total heat generation observed is shown with cooling capacity of the cryocooler in figure 3. The total heat generation is given as the sum of the electromagnetic losses and the thermal loads such as thermal radiation and heat conduction from the outside. The cooling capacity is calibrated by the temperature at the cryocooler head. The balanced temperature in figure 2 was almost equal to the temperature where the total heat generation of the coil balances to the cooling capacity in figure 3. In the case of 160 A, the total heat generation is higher than the cooling capacity in a whole range of temperature. This relation well explains the result that the thermal runaway current for the initial temperature is almost constant around 160 A in a low temperature region in figure 2. In the case of the current amplitude less than 160 A, it is also pointed out that the thermal runaway can be induced even if the total heat generation is lower than the cooling capacity.

3. Numerical simulation

3.1. Calculation of heat generation
The heat generation inside the winding is composed of ac loss and flux-flow loss in ac operation. In order to simulate the thermal situation of the coil in the ac operation, we estimated the ac loss and the flux-flow loss separately. We have already measured flux-flow loss by using E-J characteristics of Bi2223 strand and magnetic field distribution [3]. We measured the ac losses of Bi2223 strands in the temperature range of 40 to 77 K by using a saddle-shaped pick-up coil. The sample was 4 piled short strands. Sinusoidal ac magnetic field was applied in parallel or perpendicular direction to the wide surface of the piled sample.

Calculation of the total heat power generation in the ac operation of 0.5 to 5 Hz at 70 K is shown in figure 4. Here, we obtained the heat power generation as the direct sum of the losses individually estimated in perpendicular and parallel fields. The flux-flow loss becomes major component in the total heat generation with increasing current amplitude. The experimental results are well explained by the theoretical prediction in the region where the ac loss was major component of the total heat generation, while some discrepancy is marked in the region of higher current amplitude. It may come from variation in the E-J characteristics of strands in the winding process and contact resistances at the terminals of the conductor.
3.2. Numerical simulation
We carried out numerical simulation of the coil in order to study the thermal runaway of the cryocooler-cooled system by using 2-dimensional axially symmetric model and 2-dimensional thermal diffusion equation. The thermal boundary conditions are that heat flux through a cooling surface on the top flange of the former equals to the cooling capacity shown in figure 2 and that the other surfaces of the coil system are thermally insulated.

Figure 5 shows numerical simulation of temporal change in the averaged coil temperature from the initial value of 30 K in sinusoidal operation of 3 Hz with the amplitude of 190, 195, 200, 210 A. The simulation well reproduces a long-term period of gradual increase in the coil temperature up to the initiation of thermal runaway for the transport current with the amplitude slightly over a threshold. The map of stability is also given in figure 6 by the simulation. We have a semi-quantitative agreement between the numerical results and the experimental ones for the condition of thermal runaway in comparison between figures 2 and 6. The simulation result will be improved by further consideration of heat power generation and refinement of the cooling structure model.

4. Conclusion
We observed the relation between thermal runaway and the operational conditions of transport current of 3 Hz and coil temperature. The experimental results give a map of stability, including the conditions of stable operation and the initiation of thermal runaway, for the transport current and the coil temperature. In order to explain the map of stability, we estimated the heat generation and carried out numerical simulation. We have a semi-quantitative agreement between the numerical results and the experimental ones for the condition of the thermal runaway.

References
[1] Iwakuma M et al., 1999 IEEE Trans. Appl. Supercond. 9 928
[2] Ishiyama A et al., 2005 IEEE Trans. Appl. Supercond. 15 1879
[3] Miyazaki H et al., 2005 IEEE Trans. Appl. Supercond. 15 1663