Fabrication of 1kA class oxide superconducting transformer cooled by cryocooler for AC transport measurement

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Abstract

An AC current source of 1000 A class for AC transport measurements was designed and fabricated with using an oxide superconducting current transformer. Two cryocoolers were installed for cooling the transformer and a sample holder separately. A parallel conductor composed of 6 tapes was wound for a secondary winding and a transposition was performed to make the current distribution uniform in the parallel conductor. Temperatures of the transformer and the sample holder were controlled in the range of 35–50 K and 25–77K, respectively. The peak current in the secondary winding was over 1000 A in the frequency range of 1–75 Hz, when the primary peak current was 14 A.

Keywords: superconducting transformer, cryocooler, AC transport loss

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1 Introduction

Since the critical current of Bi-based superconducting tapes diminishes rapidly with increasing magnetic field at L. N_2 temperature, applications of the tapes are concentrated to the low magnetic field region. Power transformers[1] and power transmission cables[2] are examples of such applications. In these cases, a further reduction of AC loss is a key issue for realizing a competitive advantage against conventional power electricities. For this purpose, a measurement of AC transport loss of superconducting tapes is necessary. However, the critical current of Bi-based or Y-based superconductor is sometimes over several hundred ampere, and the loss measurement up to such a high AC current level is difficult.

The authors have demonstrated that superconducting current transformers are useful for a current source for such a measurement[3,4]. An AC current up to 800 A was obtained in L. N_2, when a secondary winding was shunt by a copper plate. In this study, a new AC current source operating at temperatures below 77.3 K was designed and fabricated with using an oxide superconducting current transformer cooled by a cryocooler. The current capacity was expected to be increased when operated at these temperatures. Advantages for the use of the superconducting transformer are to avoid high current leads to a sample and Joule heat at the current leads and the transformer. Hence, the stabilization of the sample temperature was expected to be easy and good. The sample temperature was also designed to be controlled by another cryocooler. The result of test operations for the current transportation and the temperature control are reported.

2 Design and fabrication

An overview of the equipment is shown in Fig.1. The size is about 600 mm in diameter and about 1000 mm in height. Two cryocoolers were installed. One is used for cooling the transformer and a Cu shield, and the other is used for cooling a sample holder. These are operated independently to each other, and the control of sample temperature is much easier. The two cryocoolers are single-stage Gifford McMahon (GM). The cooling capacity is 20 W at 40 K and the attainable lowest temperature is 25 K. The inside of the equipment is held in vacuum less than 10^{-3} Pa. The main part of the equipment is surrounded by the Cu shield of 2 mm thick and 20 layers of superinsulations to reduce a thermal radiation.

The phase of transformer is single and the operation temperature was designed to be below 50 K. An iron core with a square cross section of 31 mm $\times$ 31 mm was used to make the coupling between the primary and secondary windings better. The peak maximum current for the primary winding was set to be 15 A due to a limit of current supply, BWS40–15 (Takasago). Hence, a superconducting Bi-2223 tape was used for the primary winding. The filament number and the silver ratio was 61 and 2.0, respectively. Other major specifications are listed in Table 1. In the secondary winding 6 tapes, which were the same as the primary winding, were connected in parallel to obtain a large current capacity. Therefore, the number of turns in the secondary winding was determined as 6 from the number of transpose necessary for a uniformity of the impedance of each tape[5]. The critical current at 50 K was about 1200 A. Thus, the number of turns in the primary winding was determined as about 440, so that the secondary peak current of 1000 A is obtained when the primary peak current is about 14 A. A tertiary winding was also wound using a multifilamentary copper wire. This is used instead of the superconducting primary winding for high frequency operation, since the impedance of multifilamentary copper wire is lower than that of the superconducting tape at a high frequency. In this case, a middle tap set up in the tertiary winding is used to reduce the voltage of the winding to a half. The specifications of primary, secondary and tertiary windings are shown in Table 1. The secondary current was measured by a Rogowski coil.

The bobbin of transformer was made of FRP, and a ceramic AlN was used for flanges because of a good thermal conductivity and a poor electrical conductivity. The 18 pieces of AlN plates with 5 mm width and 1 mm thick were used for cooling channel at each layer. The flanges and plates were connected by indium sheet. An epoxy resin with high thermal conductivity was fully spread on the cooling channel and on the wires to fix and reduce the thermal conductivity.

An AlN ceramic board was used as a sample holder for stabilizing the sample temperature. A heater of 300 W in maximum was located under the ceramic board. The sample temperature is controlled by the heater and by on/off of the cryocooler. A sample such as a melt processed Y-based superconductor is fragile and an attention should be paid on the connection of the sample with the secondary winding. Especially a thermal contraction during cooling down should be considered. For this purpose, a flexible wire consisted of 40 Cu plates of 0.1 mm thick was used for the connection.

3 Operating tests

The transformer was uniformly cooled down to 35 K from room temperature in about 24 hours. In this condition, the sample holder was cooled down to 25 K. A copper plate of 58 mm $\times$ 3.0 mm$\times$ 42 mm was used instead of a sample in the current transport test. A current over 1000 A was obtained for a frequency range of 1–75 Hz. It was confirmed that 1000 A was also transported for a triangular waveform at 1 Hz. This suggests that the present equipment can also be used for a DC four probe measurement such as a critical current measurement. The current transformation ratio was estimated as 71 at 60 Hz and was slightly lower than the designed value of 73.2. Above 75 Hz the secondary current is restricted due to the voltage limitation (40 V) of the current source for the primary winding. For example, at 1 kHz the secondary current was restricted to about 100 A. When the middle tape of the Cu tertiary winding was used instead of the primary winding, the secondary current up to about 200 A was obtained due to the reduction of voltage of the tertiary winding in spite of the reduction of the transformation ratio. An observed waveform at each frequency did not show distortion nor phase shift, indicating a high coupling between the windings.

Fig. 2 shows temperature variation at each measured point during the test at various values of transport current at 60 Hz. The temperatures of the primary and secondary windings gradually increased up to 50 K in 30 minutes at 1000 A. Then, the current was decreased to 900 A and the temperature decreased to about 47 K and saturated. Therefore, the present equipment can continuously operate in the condition of transport current below 900 A. In the next, when the current was decreased to 800 A, the temperature decreased more. When the current was increased to 950 A, the temperature increased continuously. Then, the current was shut down and the transformer was cooled down from 50 K to 35 K in about 1 hour. While the transformer temperature was varied from 35–50K during the test, the sample holder temperature was almost constant at 25 K. On the other hand, when the sample holder temperature was controlled to be 77 K, the transformer temperature was almost constant at 35 K. Therefore, the transformer and sample holder are thermally independent of each other as designed.

Finally, the resistive voltage of a Cu plate connected to the secondary winding was measured by a lock-in amplifier, and the resistance was estimated as $R = 8.24 \times 10^{-7}\ \Omega$ at 73 K when the secondary current was 1140 A. On the other hand, the resistivity of Cu of $RRR = 100$ at 73 K is $\rho = 1.8 \times 10^{-9}\ \Omega$m, resulting in $R = 8.3 \times 10^{-7}\ \Omega$. Therefore, the current transportation to a Cu plate was successful, and an AC loss measurement of an oxide superconductor will be possible.

In summary, a designed AC current source with an oxide superconducting current transformer was successfully fabricated. The secondary current exceeded 1000 A in the frequency range of 1–75 Hz. The transformer and the sample holder could be thermally separated and independently controlled by using two cryocoolers. This current source will be useful for AC loss measurements of oxide superconductors.

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Figure captions

Fig. 1. Overview of the equipment using an oxide superconducting current transformer and two cryocoolers.

Fig. 2. Variation of temperatures of each points during oprating test for various values of transport current.

Table 1: Specifications of primary, secondary and tertiary windings.

	primary	secondary	tertiary
inner diameter (mmϕ)	72	95.8	103.6
thickness (mm)	9.4	0.9	3.12
height (mm)	225.5	225.5	225.5
number of turns	55×8	6	205×2
material	Bi-2223 tape		Cu
dimension (mm)	3.8×0.26		$\phi 1.06$
I_c (A)	> 50 at 77 K		—
length of conductor (m)	113	11	113

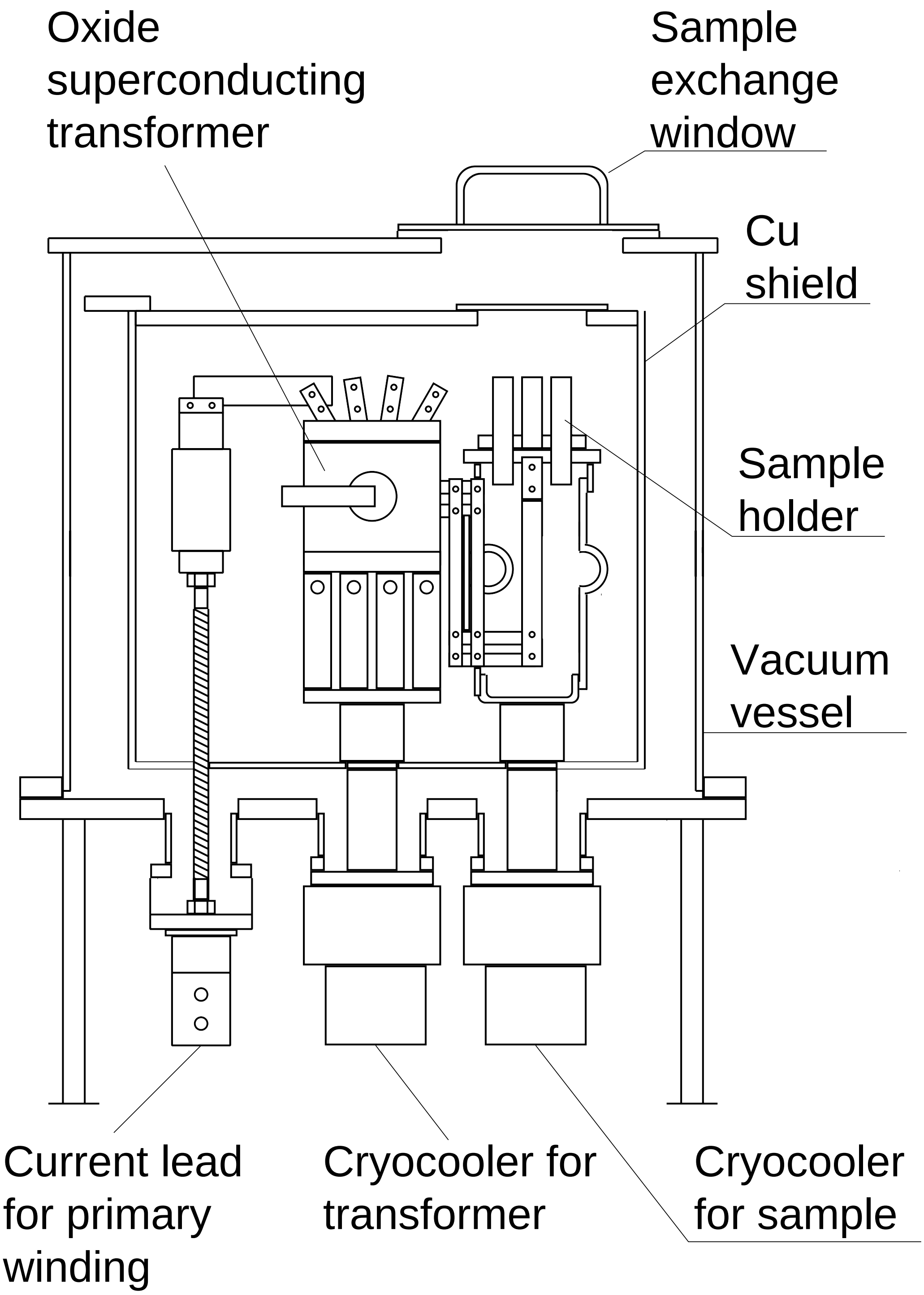

Figure 1: E. S. Otabe *et al.*

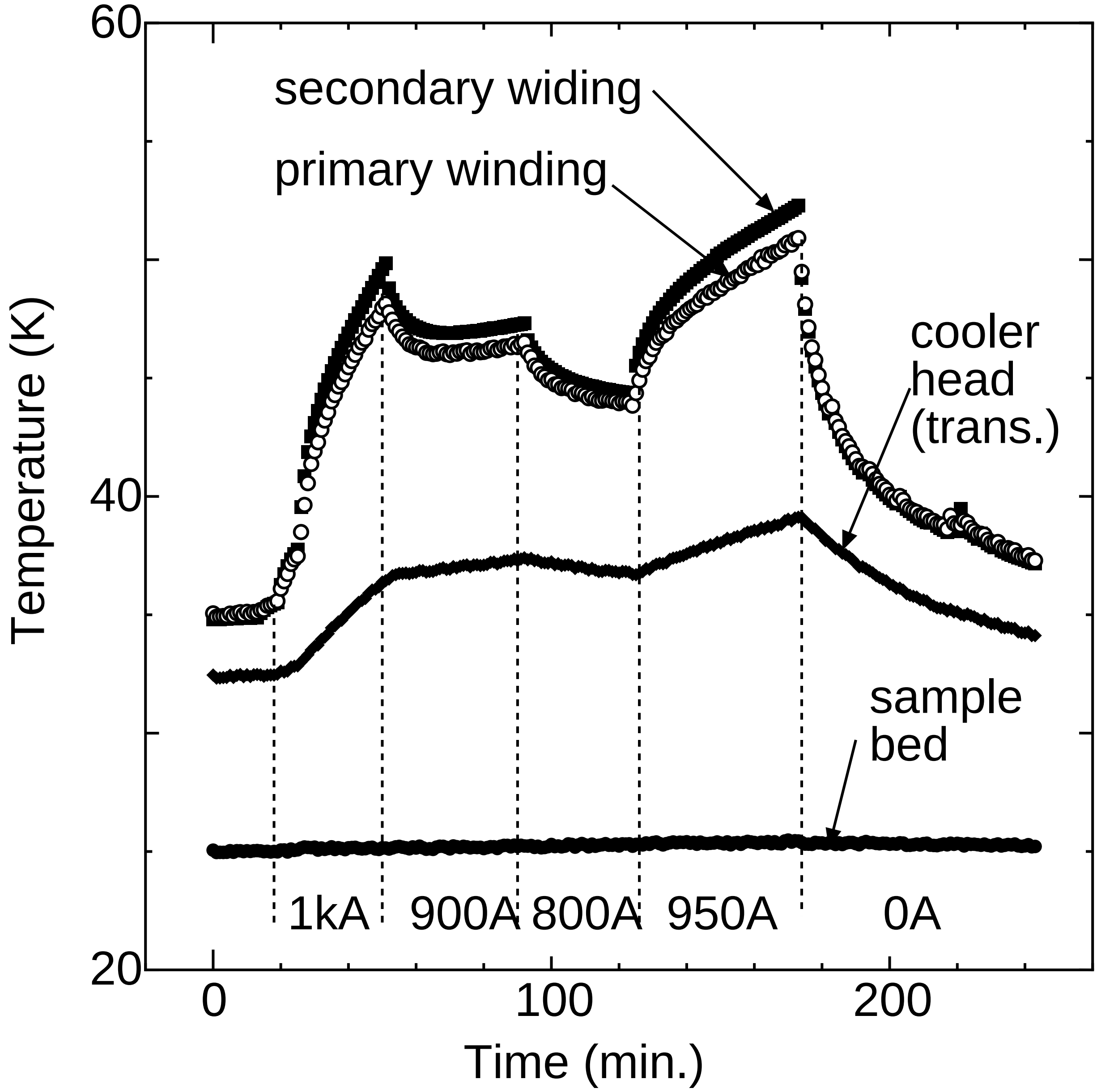

Figure 2: E. S. Otabe *et al.*