IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005

Effective Resistance of the HTS Floating Coil of the Mini-RT Project

Nagato Yanagi, Toshiyuki Mito, Tsutomu Hemmi, Kazutaka Seo, Junji Morikawa, Yuichi Ogawa, and
Masataka Iwakuma

***Abstract*—A magnetically levitated superconducting coil device, Mini-RT, has been constructed using high temperature superconductors for the purpose of examining a new magnetic confinement scheme of high-beta plasmas. The floating coil is wound with Bi-2223/Ag tapes, and it is operated in the temperature range of 20–40 K. The excitation tests of the coil were carried out and persistent current was sustained for magnetic levitation. The decay time constant of the persistent current was measured and the effective resistance of the coil cables was evaluated. The obtained resistance shows a considerable increase than that predicted by the n-value model. This might be caused by some electromagnetic effects such as the loss generation with long-lived shielding currents. This consideration was examined by measuring the magnetization of an HTS sample coil.**

***Index Terms*—Bi-2223, fusion, magnetic levitation, Mini-RT, shielding current.**

I. Introduction

In order to investigate the advanced confinement scheme of high-beta nonneutral plasmas with a new relaxation process [1], a dipole-like magnetic configuration is incorporated using a magnetically-levitated superconducting coil. The "Mini-RT" device has been constructed with a high temperature superconducting (HTS) floating coil having a diameter of 300 mm and a weight of 16.8 kg to carry out the basic experiment for plasma confinement and to develop necessary technologies for establishing reliable superconducting floating coil systems [2]. Since the floating coil has no refrigeration during magnetic levitation, it is of primary importance to have sufficient heat capacity to maintain the low temperature for realizing long magnetic levitation. In order to satisfy this requirement with the present small coil size, using HTS was determined to be the only practical solution [3]. Thus, the Mini-RT device has become one of the world first applications of HTS for fusion research.

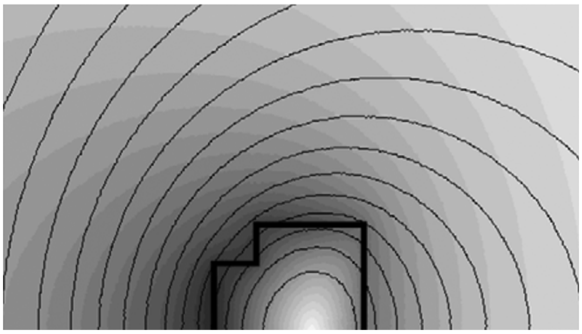

Fig. 1. Spatial profiles of the magnetic field lines within and outside the HTS floating coil of the Mini-RT device. The thick lines indicate the periphery of the HTS windings.

II. Engineering Features of the HTS Floating Coil

The floating coil of the Mini-RT device is operated in the temperature range of 20–40 K, and Bi-2223/Ag tape conductors were selected because of their high performance based on the recent technological progress [4], [5]. The nominal operation condition requires the total coil current of 50 kA, which is generated by 428 turns of solenoid windings using 420 m of an HTS tape. The tape has a critical current of 108 A at 77 K (self-field, 1 $\mu\mathrm{V/cm}$ criterion) with a relatively low silver ratio of 1.57. The insulation of the tapes was performed using Polyimide films of 50 $\mu\mathrm{m}$ thickness on both surfaces. With the nominal operation condition, the maximum magnetic field of 0.76 T is generated in the parallel direction to the tape surface at the innermost windings. The perpendicular field (maximum value: 0.51 T) becomes significant at the coil edges as is indicated by the magnetic field line traces shown in Fig. 1.

One of the engineering features of the Mini-RT floating coil is that the coil current is supplied directly from an external DC power supply using detachable feed-through electrodes. This is a remarkable difference from the floating coil of the Levitated Dipole Experiment (LDX) at Massachusetts Institute of Technology, which employs the inductive charging method using an external superconducting primary coil [6]. The direct excitation requires a persistent current switch (PCS) in the coil, and thus, an HTS-PCS was developed for the present purpose using Bi-2223/Ag tapes [7].

After the coil winding was complete, excitation tests were conducted using a liquid helium cryostat at the National Institute for Fusion Science (NIFS) [7]. The coil was installed in a tentative vacuum chamber and temperature controlled gas helium was supplied through a heat exchanger. The maximum cable current of 118 A was successfully achieved, which exceeded the

Manuscript received October 5, 2004. This work was supported by the auspices of the NIFS Collaborative Research Program and by Grant-in-Aids for Scientific Research (no. 12308019 and no. 14580532) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

N. Yanagi, T. Mito, and K. Seo are with the National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan (e-mail: yanagi@nifs.ac.jp).

T. Hemmi is with the Graduate University for Advanced Studies, 322-6, Gifu 509-5292, Japan.

J. Morikawa and Y. Ogawa are with the University of Tokyo, Tokyo 113-8656, Japan.

M. Iwakuma is with Kyushu University, Fukuoka 812-8581, Japan.

Digital Object Identifier 10.1109/TASC.2005.849104

nominal value of 116.8 A. Persistent current operations were successfully realized by confirming sufficient performance of the HTS-PCS.

After completing the excitation tests at NIFS, the HTS main coil and PCS were covered by a copper radiation shield with multi-layer insulators and installed into a stainless-steel coil case. The floating coil was then situated into the vacuum vessel (diameter 1 m) of the Mini-RT device. Socket-type current feed-through connectors are equipped in the coil and detachable electrodes are inserted for direct charging [3]. The coil-leads between the HTS coil and current feed-through connectors are made of Bi-2223 tapes with 3at%Au-doped Ag-sheath (critical current: 62 A at 77 K, self-field) in order to obtain low thermal conductivity.

In the Mini-RT device, the floating coil is cooled by cold gas helium supplied by a circulation compressor through a cold-box. The cold-box is equipped with heat exchangers which are cooled by two GM refrigerators. The total refrigeration power is 33 W at 20 K. Three sets of detachable transfer tubes are installed in the cooling circuit and the gas helium goes into the cooling pipes of the main HTS coil and PCS separately through check valves. The mass flow rate of the gas helium is set approximately at 0.5 g/s and it takes about 11 hours to cool the coil from the room temperature to 20 K.

III. EXCITATION OF THE HTS COIL AND MEASUREMENT OF TIME CONSTANT DURING PERSISTENT CURRENT OPERATIONS

A series of excitation tests have been carried out for the HTS floating coil in the Mini-RT device [8]. The excitation procedure is summarized as follows: The temperature of the HTS-PCS is raised above the critical temperature using a Manganin heater installed in the PCS windings, while reducing the gas helium flow in the PCS circuit. The coil current is then charged using an external power supply. Here, the coil current is evaluated by measuring the magnetic field at the coil center using a Hall probe. After the coil current reaches the nominal value, the PCS heater is turned off and it is cooled again. Then the power supply current is gradually reduced and a persistent current mode is achieved.

After the persistent current operation was successfully realized, the decay time constant of the persistent current was measured by continuing the cooling at the specified temperature. Two examples are shown in Fig. 2 for the coil temperature of 37 K (a) and 21 K (b). The time constant of the current decaying process is evaluated after the temperature becomes constant and for example, it is found to be about 20 hours with a cable current of 100 A at the coil temperature of 21 K. This time constant seems to be considerably shorter than the expected value (longer than 100 hours) estimated by summing up the voltage generation along the HTS cables. Here, the voltage is calculated using the effective resistance given by the n-value model.

IV. EVALUATION OF THE EFFECTIVE RESISTANCE OF THE HTS COIL FROM THE DECAY TIME CONSTANT

From the observed decay time constant of the persistent current at each timing, it is possible to determine the effective resistance of the whole windings by dividing the observed time constant by the self-inductance of the coil (87.6 mH). Fig. 3 shows the dependence of the obtained effective coil resistance on the coil current. Two temperature cases at 37 K and 21 K are plotted. It is clearly seen in Fig. 3 that the experimentally evaluated resistances are significantly higher than the expected values given by the sum of the effective resistance (based on the n-value model) and the joint resistance. Moreover, they are found to be well fitted by parabolic functions of the coil current. As is easily imagined, the resistance given by the n-value model must give a curve that increases rather sharply at a certain current level. One example with $n = 10$ case is shown in Fig. 3. On the other hand, the joint resistance is evaluated by the offset value at zero current which can be determined by the parabolic fittings of the measured coil resistances. The obtained value of 55 nΩ is in the same range as that expected by the measured joint resistance with a proto-type HTS-PCS [7].

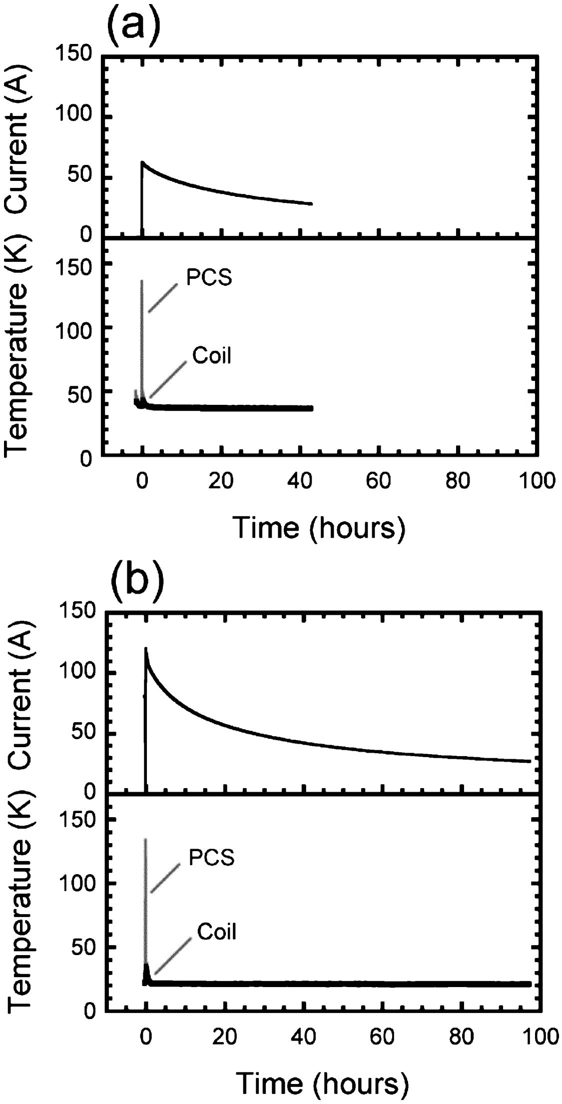

Fig. 2. Temporal decaying processes of the cable current of the HTS floating coil in persistent current mode operations at the coil temperature of (a) 37 K and (b) 21 K.

The difference between the experimentally determined coil resistance and the expected one can be clearly seen also in the voltage-current curve shown in Fig. 3(b). It is suggested that

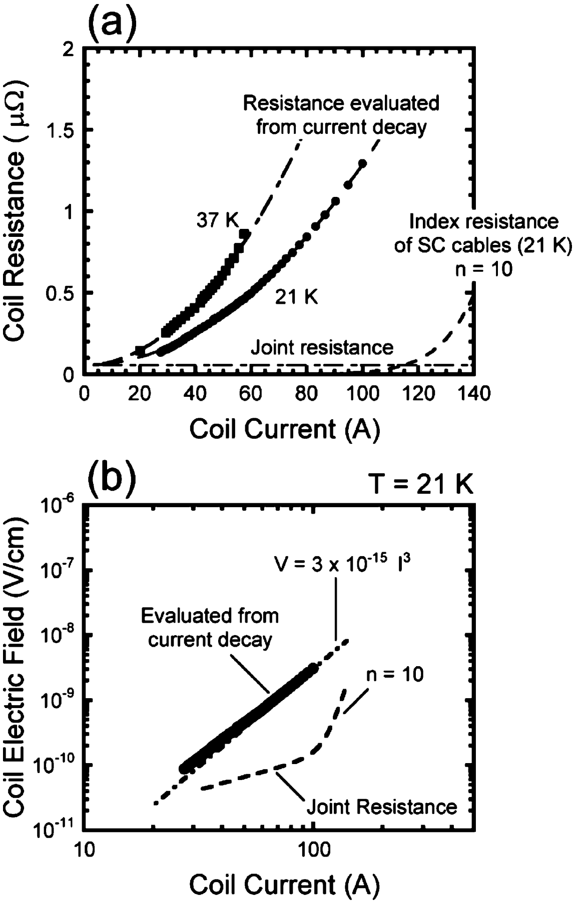

Fig. 3. (a) Dependence of the experimentally evaluated effective resistance of the HTS floating coil on the coil current. Two cases with coil temperature of 37 K and 21 K are plotted. (b) The vertical axis is converted to be the expected coil voltage by multiplying the coil resistance by the current.

this enhancement of the cable resistance is due to mechanical damages along the HTS tapes during the winding processes. However, the observed peculiar behavior, i.e., the coil resistance increases as a parabolic function of the coil current, indicates that some kind of electromagnetic effect is concerned to enhance the resistance and hence accelerate the decaying process of the persistent current. An example of this kind of dependence of resistivity can be found for normal conducting metal composites when Hall currents are induced [9].

V. Investigation of the Mechanism of Additional Loss Generation With an HTS Sample Coil

As is shown in Fig. 1, for the HTS floating coil of Mini-RT, the magnetic field is oriented perpendicularly to the tape surface at the peripheral regions of the coil cross-section. Here we consider that a large fraction of shielding current flows along the superconducting tape due to the fact that there is no twist in the present multifilamentary Bi-2223/Ag tapes. The generation of shielding currents is schematically illustrated in Fig. 4. Due to the effective resistance of the superconducting current (as is given by the n-value model), the generated shielding current is supposed to decay rather quickly in a straight cable, especially with a short length. However, when a tape is wound into a coil with many layers, the generated shielding current in each layer is supposed to mutually couple with currents in other layers. Thus, the generated shielding current might have a long time constant for its decaying process. In this respect, it might be a natural consideration that an additional loss generation is supposed to be observed in the HTS tapes with a coil configuration and this will enhance the measured effective resistance of an HTS coil and hence decreases the time constant of the current decaying process for persistent current operations.

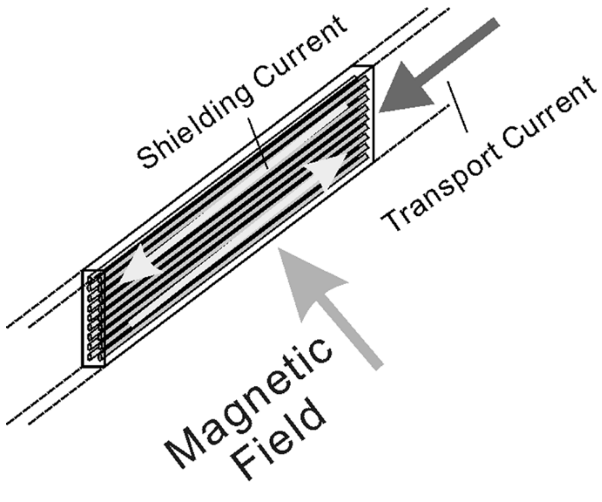

Fig. 4. A schematic illustration showing the generation of shielding current in a non-twisted multifilamentary Bi-2223/Ag tape. The external magnetic field is applied in the perpendicular direction of the tape surface.

TABLE I
Major Specifications of the HTS Sample Coil

Inner / Outer Diameter	122 / 150 mm
Coil Type	Single Pancake
Number of Turns	34.5
Superconductor	Ag-sheathed Bi-2223
Tape Width / Thickness	4.1 / 0.305 mm
Reinforcement	Stainless Steel
Critical Current (77K, s.f.)	126 A
Cable Length	14.7 m
Inductance	74 μH
Insulator	Polyimide (50 μm)

In order to investigate this scenario, we have developed a special testing device in which a pair of superconducting split coils are situated [10]. At the middle of the split coils, an HTS sample coil can be installed and uniform magnetic field is applied by energizing each split coil with opposite current directions. Here, the sample coil consists of a single pancake with a sufficiently long tape length (presently 15 m). The major specifications of the sample coil is given in Table I.

The details of the present experiment are discussed in [11] and one of its highlights is briefly introduced in the following. In the present experiment, the magnetic field above the sample coil was measured using a Hall probe and the change of magnetization of the sample coil was monitored. One of the obtained results is shown in Fig. 5(a) for the case with the background magnetic field of 0.59 T at the sample temperature of 40 K. It is clearly seen that the measured magnetic field on the tape surface shows a gradual increase with a long time constant after the external magnetic field reached the flat-top (at $t = 0$ s). It is found that the measured magnetic field on the HTS tape shows

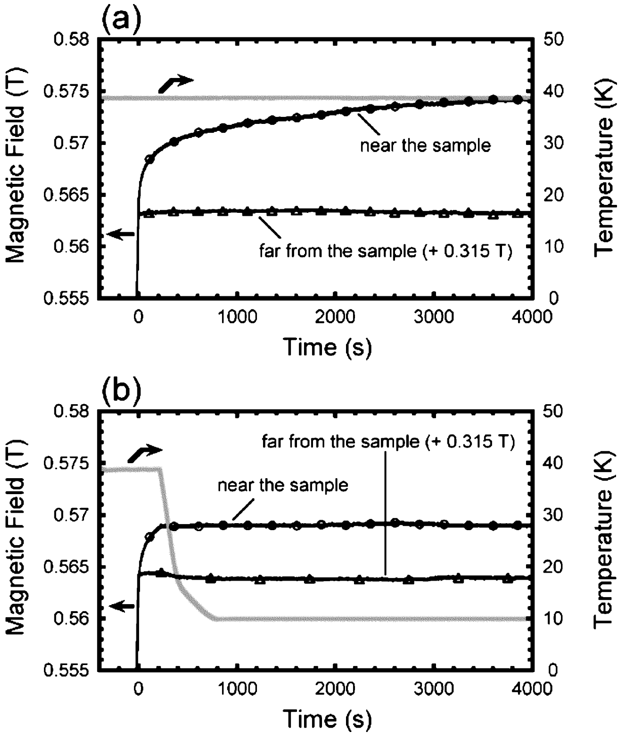

Fig. 5. Waveforms of the magnetic field measured on the HTS sample coil in the perpendicular direction of the tape surface. The external magnetic field reaches the flat-top at $t = 0$ s. (a) The sample temperature is kept at 40 K. (b) The temperature is deceased from 40 K to 10 K at $t = 200$ s.

a logarithmic increase with time. This finding seems to be very similar to the well-known logarithmic decays of magnetization observed in HTS bulk superconducting materials as well as in NbTi Rutherford cables [12].

For bulk materials, it is also known that the decaying process of trapped magnetic field can be effectively mitigated by decreasing the temperature after charging. By this analogy, the same method was applied for the present coil sample and the result is shown in Fig. 5(b). After the background field reached the flat-top with the same operation conditions for the case of Fig. 5(a), the temperature of the sample coil was decreased from 40 K to 10 K. It is then clearly seen that the magnetic field above the HTS sample becomes almost flat. This observation indicates that the decaying process of the shielding current is mitigated due to the increase of the critical current density in the HTS tape. Further analysis for the experimental results is given in [11].

The above experimental results with an HTS sample coil suggests that the enhancement of the effective resistance observed in the HTS floating coil of the Mini-RT device might be caused by shielding currents generated in an HTS tape with a coil configuration. We then consider that the decay time constant of the persistent current can be effectively prolonged by applying the same method, i.e., the coil is charged at a levitated temperature and it is cooled to the nominal temperature. This scenario will be experimentally examined with the Mini-RT coil in the near future.

VI. CONCLUSION

An internal coil device, Mini-RT, was constructed using a high-temperature superconducting (HTS) coil made of Bi-2223/Ag tapes. The effective resistance of the HTS windings was experimentally evaluated by measuring the decay time constant of the persistent current. The effective resistance shows a parabolic dependence on the coil current, which is considerably different from the expected curve based on the n-value model. It is suggested that long-lived shielding currents generate additional loss during the decaying process. The experimental results with an HTS sample coil supports this consideration.

REFERENCES

[1] S. M. Mahajan and Z. Yoshida, "Double curl Beltrami flow: diamagnetic structures," *Phys. Rev. Lett.*, vol. 81, pp. 4863–4866, 1998.

[2] Y. Ogawa, J. Morikawa, and T. Mito *et al.*, "Construction and operation of an internal coil device with a high temperature superconductor," *J. Plasma Fusion Res.*, vol. 79, pp. 643–644, 2003.

[3] T. Mito, N. Yanagi, and Y. Hishinuma *et al.*, "Engineering design of the Mini-RT device," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1500–1503, 2003.

[4] L. Masur, D. Parker, and M. Tanner *et al.*, "Long length manufacturing of high performance BSCCO-2223 tape for the Detroit Edison power cable project," *IEEE Trans. Appl. Supercond.*, vol. 11, pp. 3256–3259, 2001.

[5] T. Kaneko, T. Hikata, and M. Ueyama *et al.*, "Status of Bi-2223 tapes performance and development," *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 2465–2468, 1999.

[6] J. H. Schultz, J. Kesner, and J. V. Minervini *et al.*, "The Levitated Dipole Experiment (LDX) magnet system," *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 378–381, 1999.

[7] N. Yanagi, T. Mito, and Y. Hishinuma *et al.*, "Excitation test results of the HTS floating coil for the Mini-RT project," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1504–1507, 2003.

[8] N. Yanagi, T. Mito, and J. Morikawa *et al.*, "Experiments of the HTS floating coil system in the Mini-RT project," *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 1539–1542, 2004.

[9] H. Kaneko and N. Yanagi, "Enhancement of magneto-resistance due to Hall current in aluminum-copper composite," *Cryogenics*, vol. 32, pp. 1114–1120, 1992.

[10] T. Hemmi, A. Iwamoto, and H. Tamura *et al.*, "Experimental apparatus for measuring the characteristics of HTS tapes under controllable magnetic field, orientation and temperature," *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 1806–1809, 2004.

[11] T. Hemmi *et al.*, "Experimental Evaluation of Loss Generation in HTS Coils Under Various Conditions," *IEEE Trans. Appl. Supercond.*, vol. 15, Jun. 2005.

[12] K. Sugita *et al.*, "Study of time dependent magnetic field variation due to current redistribution in Rutherford cable," *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 255–258, 2004.