Experimental Investigation of High-Temperature Superconducting Magnet for Maglev

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ABSTRACT: The use of high-temperature superconducting wires (HTS wires) in on-board superconducting magnets for maglev has several advantages such as improvement in the stability of the superconducting magnet, improvement in reliability through simplification of the magnet structure, and decrease in the mass of the superconducting magnet and energy consumed by the on-board cryocooler. To demonstrate the applicability of HTS wires, we developed a cryocooler-free high-temperature superconducting magnet using HTS wires approximately one-quarter the size of a full-scale on-board superconducting magnet. This magnet can generate a magnetic field stronger than 1 T at a coil temperature of 50 K, and it has a cold insulation performance that can keep the coil temperature lower than 50 K for more than 8 h after initial cooling.

1 INTRODUCTION

Superconductivity was discovered 100 years ago in 1911, by a phenomenon in which the resistance of mercury suddenly became zero at 4.2 K. In 1986, the first high-temperature copper oxide superconductor was discovered. Thereafter, development of high-temperature superconducting (HTS) wires with a critical temperature higher than the liquid-nitrogen temperature of 77 K advanced. In recent years, remarkable progress has been made in the development of bismuth–strontium–calcium–copper-oxide wires (BSCCO wires) and rare-earth–barium–copper-oxide wires (REBCO wires).

For application in superconducting systems, the REBCO wire has several important advantages over the BSCCO wire: first, the critical current density at a high temperature and a high magnetic field is large; second, the mechanical strength of the tape is excellent, according to Ohsaki [1].

We believe that it is possible to realize a lightweight and reliable superconducting magnet by using a REBCO wire [2]. Currently, REBCO wires are being developed in the U.S., Japan, Germany, and Korea. Furthermore, companies in the U.S. and Japan have already started marketing REBCO wires.

2 EXPERIMENTAL INVESTIGATION OF REBCO WIRES AND COILS

2.1 Typical characteristics of REBCO wire

To consider the application of commercial REBCO wires to superconducting coils, it is necessary to confirm their quantitative transport characteristics in relation to environmental variables such as temperature and magnetic fields. However, there are few reports with such detailed data. Therefore, we developed a new device to evaluate their critical current (I) under the conditions of magnetic field (B), magnetic field angle (θ), and temperature (T) as shown in Fig. 1. The I-B-θ-T test device uses a maximum current of 1000 A, a maximum magnetic field of 5.5 T, and a minimum temperature of 10 K, as reported by Ogata [3].

Since the aspect ratio of the REBCO wire is large and the crystal structure of the superconducting layer is highly oriented, the REBCO wire has high anisotropy in terms of transport current characteristics in magnetic fields. Accordingly, the device supports the evaluation of anisotropy for the magnetic field angle θ formed between the wire surface and B (Fig. 2).

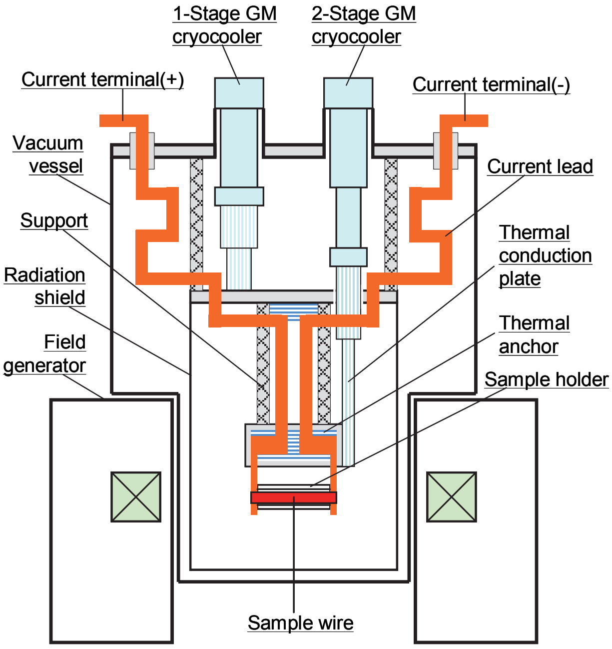

Figure 1. Schematic of the I-B-θ-T test device.

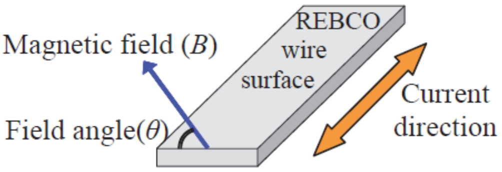

Figure 2. Definition of θ.

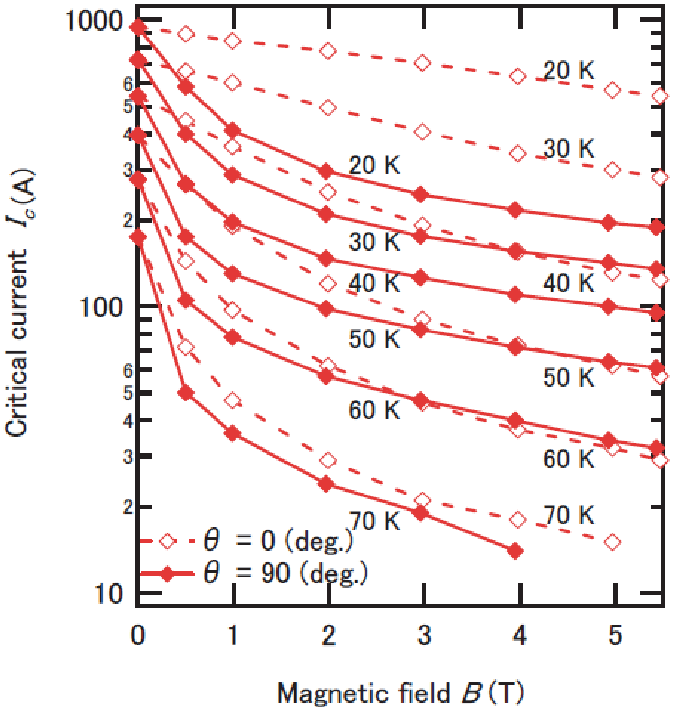

Figure 3. Magnetic field dependence of I_c for commercial REBCO wire.

Using the I-B-θ-T test device, the characteristics of the commercial REBCO wire (thickness 0.1 mm, width 4.1 mm) were evaluated. Figure 3 shows the typical magnetic field dependence of critical current (I_c) at magnetic field angles of 0 degrees and 90 degrees. This result indicates that I_c decreases with higher temperatures and at higher magnetic fields. I_c reaches its maximum for a magnetic field angle of 0 degrees and minimum for a magnetic field angle of 90 degrees. This indicates that the magnetic field angle causes a difference in I_c even under the same temperature and magnetic field conditions.

This anisotropy of I_c characteristics is problematic for the application of REBCO wires to superconducting equipment. Hence, manufacturers are currently pursuing research and development, such as doping an artificial pinning center, to address the issue.

2.2 Manufacture and evaluation of racetrack-shaped REBCO coil

Using 100 m of another commercial REBCO wire (thickness 0.2 mm, width 4.4 mm), we produced a small racetrack-shaped coil with an inside diameter of 100 mm and a straight path of 150 mm. The number of turns was 138. The coil, which was formed from a single pancake coil, was approximately one-quarter the size of a full-scale on-board superconducting coil (Fig. 4).

We carried out an I_c evaluation test on this REBCO coil using the I-B-θ-T test device under self-magnetic field conditions. Figure 5 shows the measured temperature dependence of I_c for the REBCO coil. It can be observed that I_c decreases at higher temperatures.

Based on the characteristics of REBCO wires obtained by the I-B-θ-T test device, we performed a numerical analysis to calculate I_c of the coil. Given the magnetic field angle θ and the temperature T, the magnetic field B determines the I_c of the coil. Here, B is the magnetic field that the coil generates with the transport current. We calculated two cases, θ = 0 degrees and 90 degrees, considering anisotropy of the wire characteristics. Figure 5 also shows a comparison of the test and the calculated results. The test results and the calculated results agree for θ = 90 degrees. This indicates that if the critical current characteristics of the wire and the dimensions of the coil are known beforehand, it is possible to predict the I_c characteristics of the coil. This simple estimation method is also useful for studying coil design with a certain level of performance.

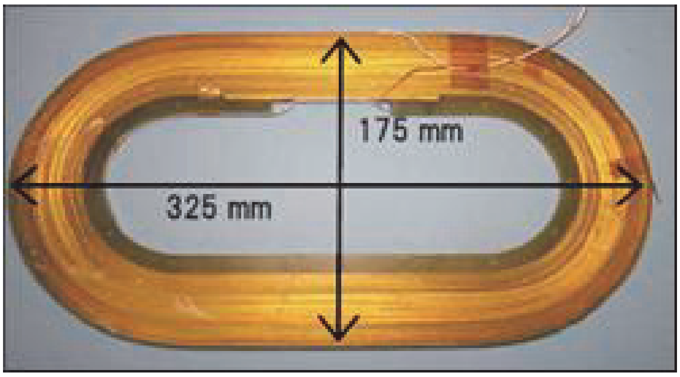

Figure 4. Racetrack-shaped REBCO coil.

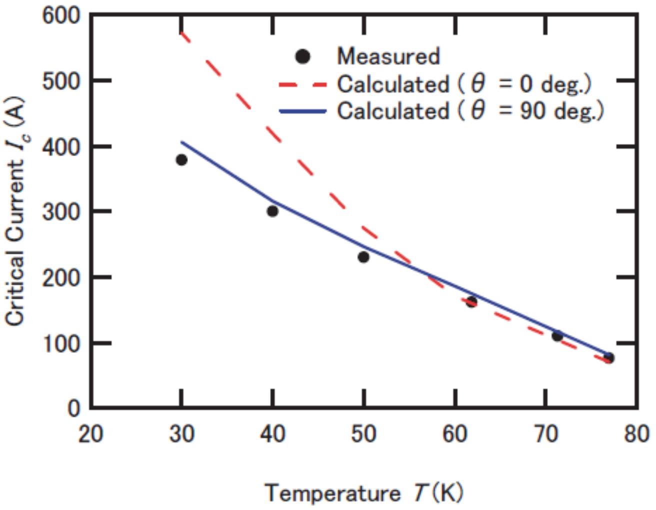

Figure 5. Temperature dependence of I_c for REBCO coil.

2.3 *Mass estimation of full-scale superconducting coils using I_c characteristics of commercial wire*

Next we tried to estimate the mass of the full-scale superconducting coils for maglev using the I_c characteristics of the REBCO wire shown in Fig. 3, and we investigated the relationship between the operating temperature and mass of superconducting coils.

We assumed that the coil cross-section is rectangular, and the central line of the coil is racetrack shaped. The long axis length of the racetrack is 1.07 m, and the short axis length is 0.5 m. The magnetomotive force is 700 kA, the wire load factor is 80%, and the winding space factor is 70%. To reduce the number of element pancake coils, the wire width is assumed to be 10 mm, and its thickness is 0.1 mm. One coil is formed by laminating six element pancake coils, and the coil width is 66 mm. The coil thickness in the radial direction depends on the I_c characteristics of the REBCO wires.

The calculation method is the same as that in a previous report [2]. The cooling temperature and the maximum magnetic field to which a coil is exposed determine the operating current of the coil. The cross-section of the coil, which determines the coil mass, is obtained from the operating current.

Figure 6 shows the estimated mass of the REBCO coil. The mass increases with an increase in the cooling temperature. In particular, at a temperature of 60 K or higher, the gradient increases rapidly. As a result, liquid-nitrogen temperature significantly increases the mass of the coil, reducing performance. However, the mass of the coil with a cooling temperature of 40 K or less may be lighter than that of the current low-temperature superconducting coil for maglev. Moreover, it is not difficult to cool a coil to 40 K with a cryocooler. Consequently, we concluded that it is possible to construct a full-scale on-board superconducting magnet for maglev even with the performance of the current commercial REBCO wire.

The dotted line in Fig. 6 shows the result calculated using the data of the short wire sample with high I_c performance, as measured by Holesinger and Civale at Los Alamos National Laboratory (LANL) [4]. Since these are experimental data, a commercial wire may also have such a performance level in the future. In this case, the mass of the coil with a cooling temperature of 50 K or less will be lighter than that of the current low-temperature superconducting coil for maglev. The heat capacity of the material increases rapidly with an increase in temperature. In case of copper, the heat capacity at 50 K is approximately 1,000 times greater than that at 4 K. In other words, temperature rise of superconducting coils decreases to 1/1000. We now propose a new concept of a superconducting magnet: the "cryocooler-free superconducting magnet," described below.

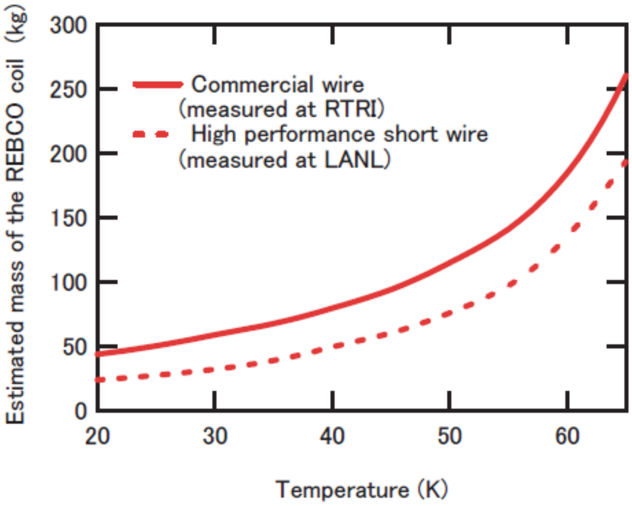

Figure 6. Estimated mass of the REBCO coil as a function of the cooling temperature.

3 TRIAL MANUFACTURE AND TEST OF CRYOCOOLER-FREE HTS MAGNET

3.1 Concept and target performances

The purpose of this study is to evaluate the possibility of using a cryocooler-free HTS superconducting magnet for maglev.

We assumed the following operations of the magnets: the on-board magnets keep HTS coils at a low temperature of less than 50 K with their heat capacity during the maglev operation and the magnets are recooled in a rail yard. Therefore, the on-board magnets maintain the coil temperature to less than 50 K for several hours. The operational temperature range of the magnets is from 20 K to 50 K.

To confirm the basic characteristics of the cryocooler-free HTS magnet that uses the REBCO wire, a small-scale magnet was manufactured for trial. This small-scale HTS magnet cannot be used for running maglev but can be used to verify the possibilities of using REBCO wires for the coils. The magnet had the following properties:

1) Detachable cooling system and power supply, which means that the cooling system is unnecessary during the magnet's operation and some closed loop current structure is present in the magnet.
2) More than 1 T of magnetic field at the coil temperature of 50 K, which means that the magnet can generate a magnetic field of the same order to the superconducting coils for maglev of 5 T.
3) More than 8 h of Maintenance time while the coil temperature is less than 50 K after disconnection from the cooling system, which means that the magnet keeps its coil temperature under 50 K during the daytime by using its own heat capacity after disconnection from the cooling system.

3.2 Specifications

Table 1 shows the specifications of the small-scale HTS magnet that uses the REBCO wire. Figure 7 shows the external view of the magnet, and Fig. 8 shows the schematic cross-section of the magnet. We used REBCO wire with a 4.1 mm width, 0.1 mm thickness, and 100 m length to produce each pancake coil. The shape and the size of the inner circumference of the coils are the same as those of the coil in Fig. 4, and the size of the coils is approximately 1/4th that of a full-scale coil. Four stacked pancake coils are installed in the magnet. According to the design, the magnetic field generated by the stacked coils reaches a maximum of 1 T at an operating current of 86 A.

We applied the internal piping structure to the magnet for cooling the stacked coils and placed activated carbon on the coils as an adsorbent (Fig. 8). By letting a low temperature helium gas flow through the piping, we can reduce the initial temperature of the coil to 20 K or less. The external cooling system can be detached at the port of internal piping. The power supply system for energizing the coil can also be detached after constructing the closed loop current circuit by handling the mechanical switch.

Table 1. Specifications of small-scale HTS magnet.

Wire type (process)	REBCO wire (Metal Organic Chemical Vapor Deposition)
Width/Thickness	4.1 mm/0.1 mm
Minimum I_c	112 A (at 77 K, self field.)
Coil shape (pancakes)	Racetrack (four single pancakes)
Outer/Inner diameter	150 mm/100 mm
Straight length	150 mm
Turns	562 turns
Tape length	400 m
Inductance	97 mH
Rating current	86 A
Magnet structure	Coil + Coil case + Radiation shield + Multilayer insulation + Outer vessel
Cooling method	Flow of gas He in internal piping
Adsorbent	Activated carbon
Initial cooling temperature	<20 K
Magnetization method	Closed current mode by mechanical switch
Mechanical switch	Material: Cu + In plating
	Resistance: <1 μΩ at 77 K
Mass	52 kg

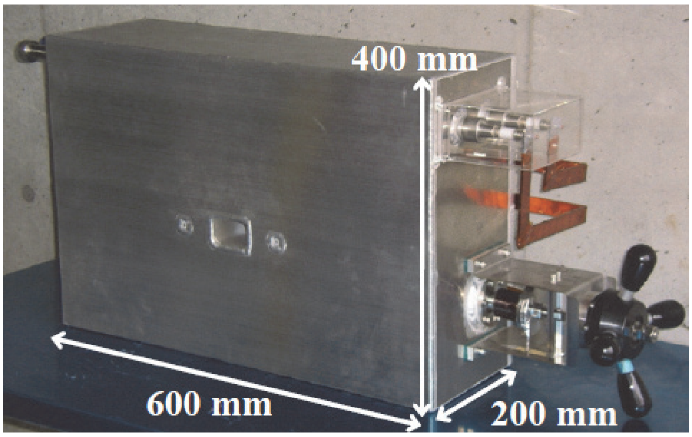

Figure 7. Cryocooler-free HTS magnet.

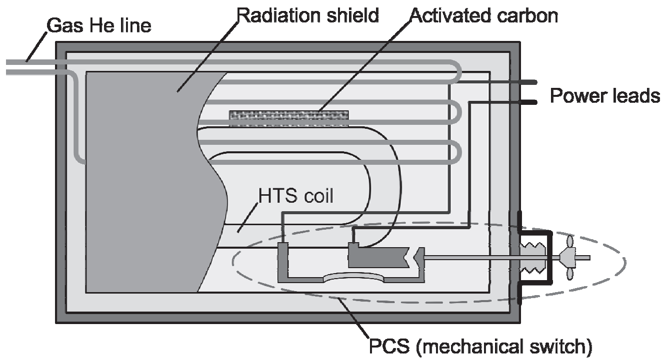

Figure 8. Schematic cross-section of cryocooler-free HTS magnet.

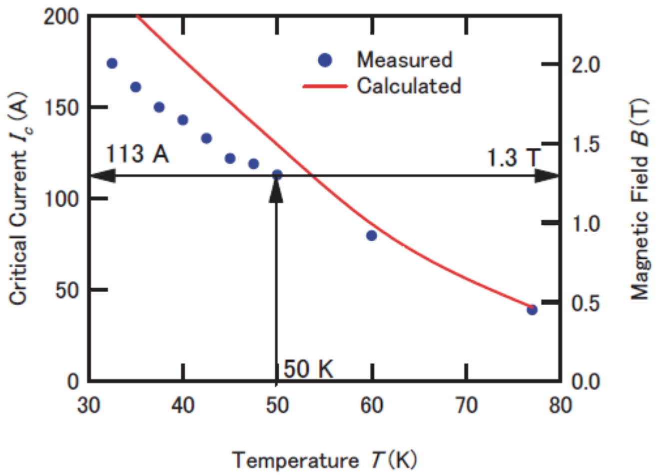

Figure 9. Temperature dependence of I_c and maximum magnetic field for stacked REBCO coils.

3.3 I_c characteristics of stacked REBCO coils

The I_c characteristics of REBCO coils for a small-scale HTS magnet were evaluated. Figure 9 shows the temperature dependence of I_c and the maximum magnetic field for the stacked REBCO coils. I_c at 50 K was 113 A, and at 113 A, the magnetic field of 1.31 T on the coil was estimated to be the maximum. The test results show that the target performance of more than 1 T was attained at 50 K.

Figure 9 also shows the calculated I_c of the stacked REBCO coils. Comparison of the calculated value with the measured data shows that the measured data is value lower than the calculated value in the low-temperature region. This degradation of I_c seems to occur because of the manufacturing method used for the four stacked single pancake coils. Takematsu reported that the REBCO pancake coil properties substantially degraded because of epoxy impregnation [5]. A manufacturing process that does not cause degradation in I_c properties is a significant subject for an HTS magnet that uses REBCO wires. However, we believe that a solution to this problem will be possible through the selection of an appropriate material in the future.

3.4 Traces of coil temperature and magnetic field of cryocooler-free HTS magnet

After the initial cooling of the coil to less than 20 K, the small-scale HTS magnet was separated from the cooling system. The magnet was also disconnected from the power supply after energizing the coil with a rating current of 86 A for a magnetic field of 1 T by operating the mechanical switch.

Figure 10 shows the test results of the coil temperature after separation from the cooling system. The result indicates that the cold insulation property from 20 K to 50 K of the coil is more than 9 h. In this respect, activated carbon in the magnet has an important role as an adsorbent; for example, in the preliminary test with no activated carbon, the cold insulation property of the magnet was less than 6 h. Another evaluation of the cold insulation characteristics also confirmed that activated carbon is essential for an HTS magnet, as reported by Mizuno [6]. The test result shows that cold insulation property achieved the target performance, which is maintaining cold insulation for more than 8 h while the coil temperature is lower than 50 K after disconnection from the cooling system. For a full-scale magnet for maglev, the cold insulation time from 20 K to 50 K would be 1 day because of the scale effect. Heat leak is roughly proportional to the square of a size, and heat capacity is! proportional to the cube of a size. Therefore,! temperature rise is in inverse proportion to a size! [6].

Figure 10 also describes the magnetic field on the coil. Because it seemed that decrease in the magnetic field was rather large, we calculated the resistance of the closed loop current circuit consisting of the coil and the mechanical switch. The estimation result of the circuit resistance was 3.2 μΩ. The resistance of the mechanical switch was less than 1 μΩ; hence, other factors such as the connection resistance of the circuit seemed to be dominant.

To realize a practical superconducting magnet with a persistent current mode, the high circuit resistance of 3.2 μΩ should be reduced. The reduction of the electric resistance of the mechanical switch and the connections on the closed circuit is the fundamental requirement for suppressing decrease in the magnetic field.

However, it is possible to increase the time constant of this closed circuit by reducing the connection resistance and improving the performance of the coil. Moreover, since the self-inductance L becomes large for full-scale coils, a time constant $\tau = L/R$ of the magnetic field generated by a coil can also become relatively large.

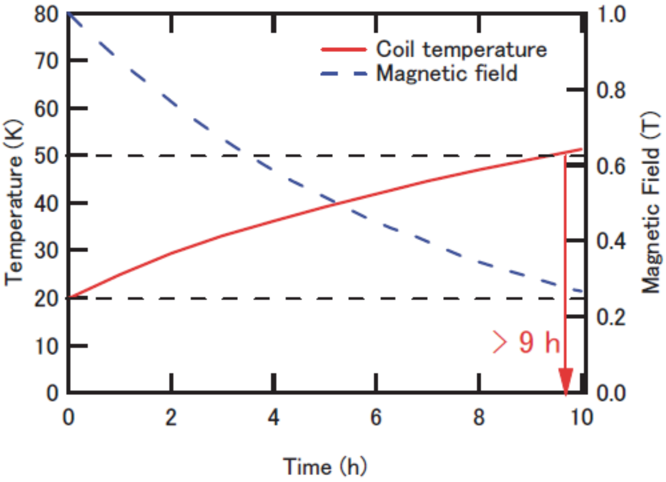

Figure 10. Traces of coil temperature and magnetic field after separation from the cooling system and power supply.

4 SUMMARY

By applying the REBCO wire to the superconducting magnet for maglev, many characteristics can be improved, such as stability of the superconducting state, reduction of the mass of the superconducting coils and the cryocooler, and reliability with a simplified structure of the magnet.

Using the *I-B-θ-T* test device, we evaluated I_c characteristics of a commercial REBCO wire.

Next, we manufactured and evaluated a racetrack-shaped REBCO coil. Based on the characteristics of REBCO wires obtained by the *I-B-θ-T* test device, we performed a numerical analysis to calculate I_c of the coil. We found that the test and calculated results were consistent.

We also tried to estimate the mass of the full-scale superconducting coils for maglev using the I_c characteristics of the REBCO wire. The results indicate that the mass reduction of the coil could be attained with the cooling temperature of 40 K or less. Consequently, we concluded that it is possible to construct a full-scale on-board superconducting magnet for maglev even with the performance of the current commercial REBCO wire.

According to the results of the experimental and scientific investigations, we proposed the new concept of a superconducting magnet: a “cryocooler-free superconducting magnet.” We also manufactured a small-scale HTS magnet for verifying the possibility of coils using REBCO wires with the features of a detachable cooling system and power supply. The following basic characteristics of the magnet were confirmed:

1) Magnetic field of more than 1 T was verified on the coil at 50 K.

2) The cold insulation property from 20 K to 50 K of the coil temperature with activated carbon was almost 10 h.

By applying these results, we are developing an HTS magnet of 5 T using REBCO wires for the next stage.

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