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First Performance Test of the Cryogenfree Hybrid Magnet

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***Abstract*—We are now constructing a cryogenfree 23 T hybrid magnet at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University. At present, an outer section coil employing NbTi multifilamentary wires for a cryogenfree superconducting magnet of the hybrid magnet was combined with an inner 15.5 T water-cooled resistive magnet, and was tested as the world's first cryogenfree hybrid magnet. The NbTi coil with 491 mm inner diameter and 584 mm outer diameter generated 4.59 T at 198 A, and the central magnetic field of 20.0 T was generated in a 52 mm room temperature experimental bore. The magnetic force field of 2030 T^2/m was obtained, and a piece of paraffin was levitated at 1200 T^2/m. Using a CO_2 laser combined with the cryogenfree hybrid magnet, a containerless melting experiment in magnetic levitation was demonstrated easily for paraffin.**

***Index Terms*—Cryogenfree superconducting magnet, high magnetic field, hybrid magnet, magnetic levitation.**

I. Introduction

THE construction of a static high field magnet at the High Field Laboratory for Superconducting Materials (HFLSM), Institute for Materials Research, Tohoku University started in 1981, and the Japanese first hybrid magnet with a 52 mm room temperature bore generated 20 T in 1983. This hybrid magnet upgraded the highest magnetic field to 23 T the following year [1]. The 23 T hybrid magnet, consisting of an outer 7.5 T superconducting magnet and an inner 15.5 T water-cooled resistive magnet, has been utilized very frequently, and repeated 2250 times the total run in fields up to 23 T for 17 years by the fiscal year 2000.

A hybrid magnet has the advantage of a large magnetic force produced by the product of the magnetic field and its field gradient. The magnetic force field of 2500 T^2/m was obtained by the 23 T hybrid magnet. The magnetic levitation against gravity is easily possible in 2500 T^2/m for many diamagnetic materials such as water and glass.

HFLSM succeeded in demonstrating, for the first time, a containerless melting experiment of glass in the microgravity state due to magnetic levitation [2]. It is considered that a large magnetic force produced by a hybrid magnet will become more and more important for new materials development research in future.

On one hand, the operation of a 23 T hybrid magnet needs a large amount of liquid helium for an outer wide bore superconducting magnet. So far, a superconducting magnet for a 23 T hybrid magnet was precooled from room temperature to 20 K using a Stirling-type PGH105 cryocooler. After precooling, 500 liters of liquid helium were needed to lower the coil down to 4.2 K and 150 liters of liquid helium above the coil had to be stored for magnet operation. Furthermore, 300 liters of liquid helium a day had to be charged to compensate the liquid helium evaporation due to transport currents and ac loss generated by changing the magnetic field. The total consumption of liquid helium in the 23 T hybrid magnet operation amounted to more than 510 000 liters for 17 years. In addition, a lot of work and enormous time were necessary for supplying a large amount of liquid helium.

On the other hand, HFLSM has successfully developed various kinds of cryogenfree superconducting magnets, since the world's first practical cryogenfree superconducting magnet was demonstrated in 1992 [3]. This was also the first practical application of high temperature superconducting current leads. A cryogenfree superconducting magnet makes rapid progress, and is expanding into a wide bore cryogenfree superconducting magnet.

In the above-mentioned situation, we intended to develop a cryogenfree 23 T hybrid magnet [4]. This paper describes the first performance test of a cryogenfree hybrid magnet consisting of an outer cryogenfree superconducting magnet and an inner water-cooled resistive magnet.

II. Characteristics of the Cryogenfree 23 T Hybrid Magnet

In order to save hundreds of thousands of liters of liquid helium for a hybrid magnet operation at HFLSM, the traditional 23 T hybrid magnet using liquid helium was replaced by a newly developed wide bore cryogenfree hybrid magnet. Table I lists the coil parameters. The wide bore cryogenfree superconducting magnet is divided roughly into an outer section coil and an inner section one.

The traditional cryogenic stability concept, based on the presence of liquid helium, cannot be applied to the thermal stability of cryogenfree superconducting magnets operated in a vacuum atmosphere. From previous experimental results [5], we found that the current sharing appearance, under the cryocooled condi-

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TABLE I
COIL PARAMETERS OF A WIDE BORE CRYOGENFREE SUPERCONDUCTING MAGNET

		inner section coil	outer section coil
inner diameter	[mm]	400	491
outer diameter	[mm]	461	584
coil height	[mm]	450	450
operation current	[A]	145	198
contributed field	[T]	3.4	4.6
central field	[T]	8.0	4.6
maximum field	[T]	8.6	5.3

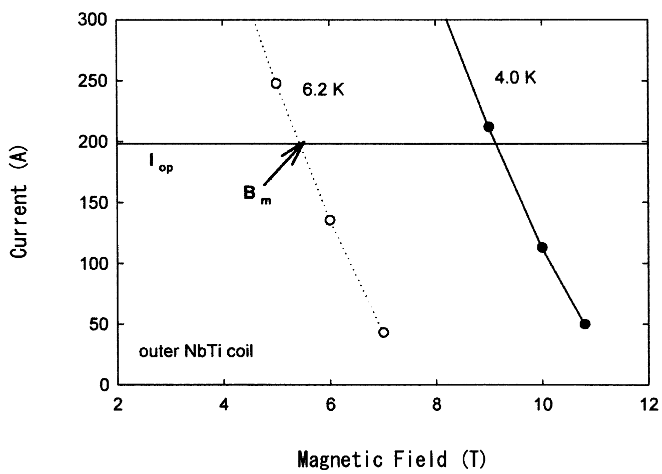

Fig. 1. I_c-vs-B characteristics for a NbTi section coil.

tion, inevitably leads to a coil quench. This results in adopting the temperature margin concept as the thermal stability for a cryogenfree superconducting magnet. Since the recovery to the superconducting state from the current sharing, similar to that under a liquid helium immersed condition, is not expected under a cryocooled condition, the temperature margin concept gives the allowance to meet the current sharing occurrence at a certain temperature rise. The temperature margin basically corresponds to the current margin concept [6].

Here, we focus on the outer NbTi coil. Temperature margin is a severe condition for NbTi. Fig. 1 shows I_c-vs-B properties in the outer NbTi subdivided coil at the maximum field of $B_m = 5.3$ T. The load ratio of $I_{\rm op}/I_c$ (4.0 K) is 67% for the NbTi coil. Since the current sharing temperature is estimated to be 6.2 K for NbTi, the temperature margin is 2.2 K as the cryogenfree superconducting magnet is operated at 4.0 K. In the case of simultaneous magnetic field sweep at the rate of 0.3 A/s for both outer and inner section coils, the hysteresis loss of 2.95 W is added to the second stages of GM-cryocoolers. As the result, the heat load at the second stages amounts to 4.22 W. Since four GM-cryocoolers with refrigeration power of 1 W at 4 K per a cryocooler are used, the temperature rise is less than 0.1 K at temperatures above 4 K. Therefore, the temperature margin of 2.2 K is sufficient.

Fig. 2 shows the schematic illustration of electrically subdivided coils for the outer NbTi section coil. The inductance is 64 H for the outer section coil and 36 H for the inner section coil.

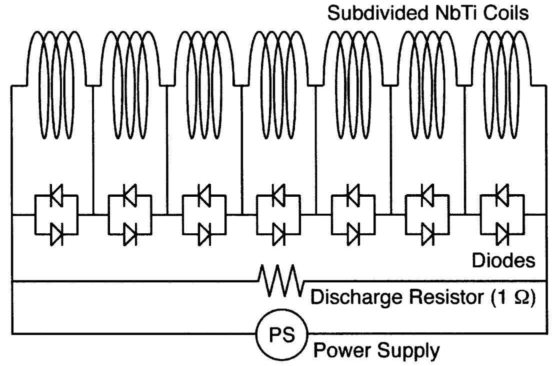

Fig. 2. Electrically subdivided coils in the outer NbTi section coil for coil protection.

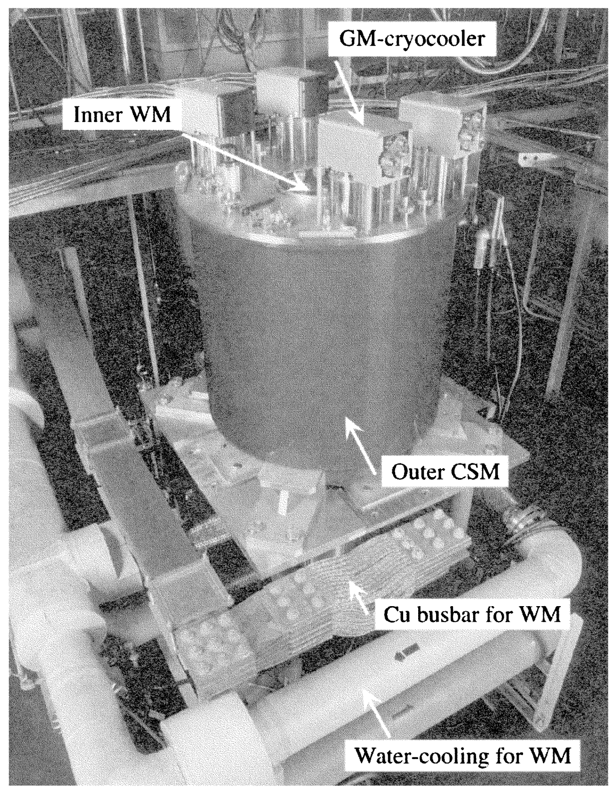

Fig. 3. Photograph of the cryogenfree hybrid magnet. CSM:cryogenfree superconducting magnet, WM:water-cooled magnet.

The total inductance including mutual inductance of 33 H is 166 H. For quench protection, each coil is designed to be subdivided electrically through protection diodes to reduce the maximum induced voltage below 1.5 kV between the neighboring coils. In addition, for a cryogenfree superconducting magnet operated in a vacuum atmosphere, the good electric insulation condition is expected.

Fig. 3 shows the constructed cryogenfree hybrid magnet at HFLSM. A water-cooled resistive magnet, which generates 15.5 T in a 52 mm room temperature experimental bore, is combined with the cryogenfree superconducting magnet. The photograph clearly exhibits a large electric busbar with the electric power of 23 kA and 350 V and a large water-cooling system with the flowing rate of 350 m^3/h at 20 bar for the water-cooled magnet. The cryogenfree hybrid magnet is designed to generate 23 T in

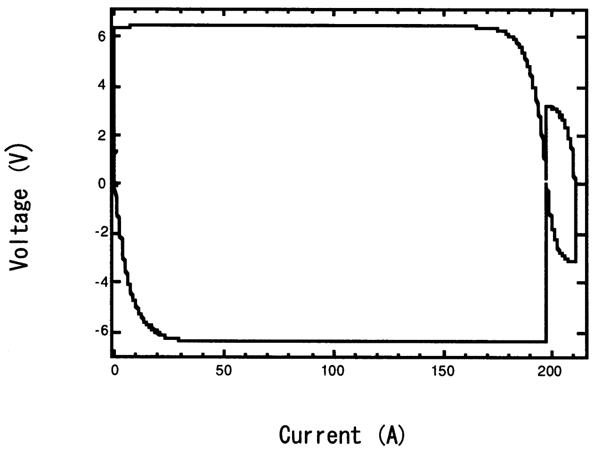

Fig. 4. Characteristics of coil voltages and coil currents.

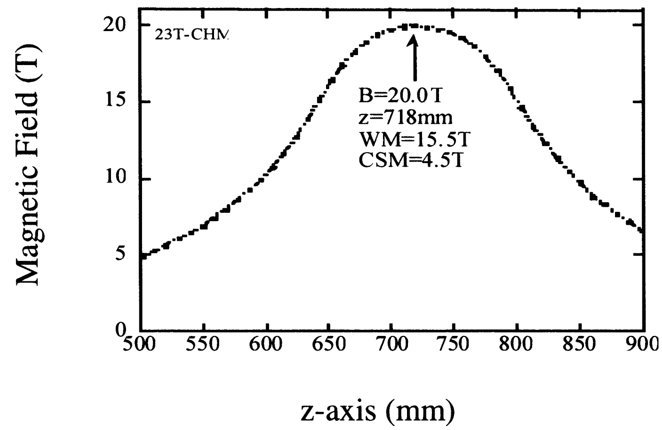

Fig. 5. Magnetic field distribution in a central z-axis direction of the 20 T cryogenfree hybrid magnet.

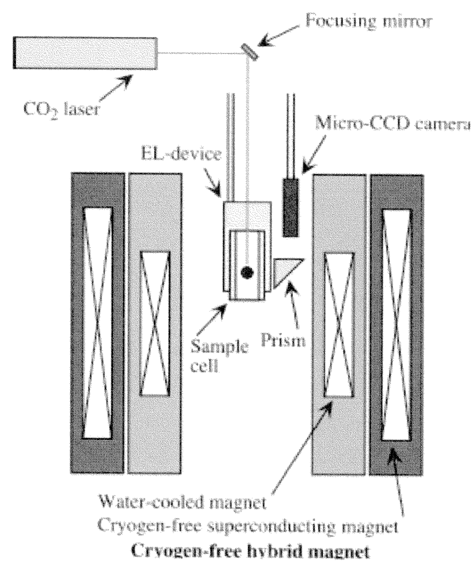

Fig. 6. Laser furnace system combined with the cryogenfree hybrid magnet.

a 52 mm room temperature bore under a backup field of 7.5 T in a 360 mm room temperature bore by a cryogenfree superconducting magnet. It is noteworthy that a cryogenfree hybrid magnet is made so compactly, and is $1/2$ as small as the traditional 23 T hybrid magnet using liquid helium.

III. First Performance Test

The outer cryogenfree superconducting magnet was cooled down to 3.15 K, after the precooling time of 110 h from room temperature. Since the inner Nb_3Sn section coil of the wide bore cryogenfree superconducting magnet was unfortunately damaged during training, it is being replaced. Therefore, as the first step of the performance test, the outer NbTi section coil of the wide bore cryogenfree superconducting magnet was energized at the current sweep rate of 0.1 A/s, and generated 4.59 T at 198 A. The coil temperature increased from 3.15 to 3.48 K during magnetic field sweep. The temperature rise of about 0.3 K in the range of 3.0 to 3.5 K corresponds to the thermal input of 0.25 W per a cryocooler. This means that the ac loss of about 1 W was cooled by four GM-cryocoolers within 0.3 K at temperatures below 3.5 K. After increasing the magnetic field up to 4.59 T, the operation current was decreased at 0.15 A/s. The voltage generated at both ends of the outer section coil was 9.6 V. Fig. 4 shows the coil voltage and coil current at the ramp rate of 0.1 A/s. Finally, the outer section coil was energized at fields up to 4.9 T at 211 A at 0.05 A/s. During magnetic field ramping, the outer section coil occurred a quench at 192 A, due to training, and the coil temperature was raise to 50 K. After cooling by GM-cryocoolers, the outer section coil was energized again. The decay time from 192 A to 0 A was about 8 s and the time constant $\tau = 2.6$ s was derived from the first steep decay curve.

The performance test of a hybrid magnet mode combined with the water-cooled resistive magnet was carried out for the first time. When a water-cooled magnet was energized at a current ramp rate of 20 A/s as a 20 minutes mode up to 23 kA, the induced voltage in the cryogenfree superconducting magnet through mutual inductance between the superconducting magnet and the water-cooled magnet was 1.8 V. This means that the mutual inductance is 90 mH. However, in the case that the water-cooled magnet happens to fail in 0.16 s from the maximum current of 23 kA, the superconducting magnet does not couple with such a very fast decay fortunately. This is because the decay time constant of the cryogenfree superconducting magnet is as long as 2.6 s. When the water-cooled magnet happens to fail from 23 kA, the induced current in the cryogenfree superconducting magnet is related with the magnetic flux conservation law. The induced current I is given in the form of $I = (M/L)I_{\mathrm{op}}$, where M is the mutual inductance, L the inductance of the superconducting magnet, and I_{op} the operation current of the water-cooled magnet. It is estimated that the induced current in the cryogenfree superconducting magnet is 32 A and the voltage of 32 V appears at a protection resistor of 1 Ω in the power supply.

Fig. 5 shows the magnetic field distribution measured by a Hall probe in the z-axis direction of a 52 mm room temperature bore. We succeeded in generating 20.0 T by the world's first cryogenfree hybrid magnet, consisting of an outer 4.5 T cryogenfree superconducting magnet and an inner 15.5 T water-cooled resistive magnet. From the field distribution, the magnetic force field of 2030 T^2/m was obtained. Since water and paraffin are levitated against the gravity at 1400 T^2/m and 1200

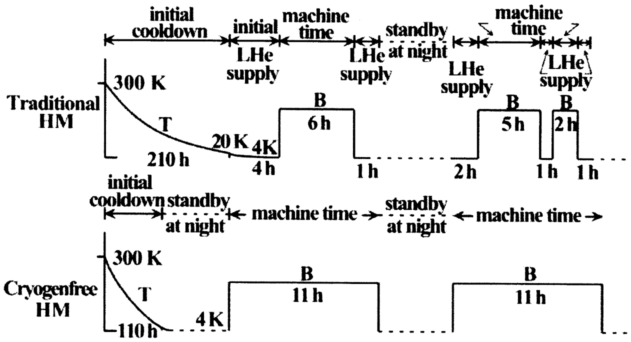

Fig. 7. Comparison of the operation mode between the traditional hybrid magnet and the cryogenfree hybrid magnet.

T^2/m, respectively, a 20 T cryogenfree hybrid magnet can provide a large magnetic force field enough to levitate diamagnetic materials. In order to develop a new processing, a CO_2 laser furnace was installed into the 20 T cryogenfree hybrid magnet. Fig. 6 illustrates a CO_2 laser system for a magnetic levitation investigation. A containerless melting experiment was carried out for paraffin, in order to study a thermocapillary convection [7]. It is of importance for containerless melting in the microgravity state to control such a convection.

Fig. 7 shows the outstanding difference of operation modes between the traditional 23 T hybrid magnet using liquid helium and the newly developed 20 T cryogenfree hybrid magnet. One notes that the machine time is extremely enlarged using a cryogenfree hybrid magnet. In particular, a cryogenfree hybrid magnet no longer needs a troublesome handling time for liquid helium supply. In the next step, an inner 3.5 T Nb_3Sn section coil has to be added consisting of a wide bore 8 T cryogenfree superconducting magnet, and we will establish a 23 T cryogenfree hybrid magnet.

IV. Conclusion

The first performance test of the cryogenfree hybrid magnet was carried out, and the central magnetic field of 20 T was generated in a 52 mm room temperature bore. The magnetic force field of 2030 T^2/m was easily obtained. The magnet will be upgraded to a 23 T cryogenfree hybrid magnet, consisting of an outer 7.5 T cryogenfree superconducting magnet and an inner 15.5 T water-cooled magnet, and will become a quite convenient tool for magnetic levitation.

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