Construction of the Cryogen-Free 23 T Hybrid Magnet

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Construction of the Cryogen-Free 23 T Hybrid Magnet

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***Abstract*—In order to settle problems requiring a large amount of liquid helium and limiting the operation time for a wide bore superconducting magnet of a hybrid magnet, a cryogen-free 23 T hybrid magnet is being constructed at the High Field Laboratory for Superconducting Materials for the first time. An outer compact superconducting magnet is wound with highly strengthened CuNb/Nb_3Sn multifilamentary wires and is refrigerated conductively by GM-cryocoolers. The maximum stress value of 210 MPa was designed for the CuNb/Nb_3Sn coil. The cryogen-free superconducting magnet will be operated using dual power supplies independently, and has potential to generate central fields of 4.59 T at 198 A for the outer section NbTi coil and 3.41 T at 145 A for the inner section CuNb/Nb_3Sn coil. When the cryogen-free 7.5 T superconducting magnet with a 360 mm room temperature bore is combined with an inner 15.5 T water-cooled resistive magnet, a cryogen-free hybrid magnet will achieve 23.0 T in a 52 mm room temperature experimental bore.**

***Index Terms*—Cryogen-free superconducting magnet, CuNb reinforcing stabilizer, high magnetic field, hybrid magnet.**

I. INTRODUCTION

RECENTLY, new processing in the gravity-free state using high magnetic fields has been demonstrated for materials development. A hybrid magnet consisting of an outer superconducting magnet and an inner water-cooled resistive magnet is surely indispensable to realization of a gravity-free condition for diamagnetic materials [1]. A wide bore superconducting magnet of a hybrid magnet, however, has some problems such as a large amount of liquid helium for operation and a shortly limited working time due to frequent liquid helium supply. If these problems can be solved, new materials development in high magnetic fields must be greatly advanced.

On the other hand, we have intended to develop the next phase multifilamentary Nb_3Sn superconducting wires with both high strength and small wire diameter. A newly developed Nb_3Sn wire reinforced with high strength and good electrical conductivity CuNb composite stabilizer instead of traditional Cu stabilizer is now available as practical long-length wires [2]. It is possible for highly strengthened Nb_3Sn wires to overcome a huge electromagnetic stress level up to 300 MPa like NbTi alloy superconductors.

TABLE I
CRYOGEN-FREE WIDE BORE SUPERCONDUCTING MAGNET FOR A 23 T HYBRID MAGNET

		magnet system	inner coil	outer coil
inner diameter	**(mm)**	**ϕ 400**	**ϕ 400**	**ϕ 491**
outer diameter	**(mm)**	**ϕ 584**	**ϕ 461**	**ϕ 584**
coil height	**(mm)**	**450**	**450**	**450**
inductance	**(H)**		**35.6**	**63.4**
wire materials			**CuNb/ Nb_3Sn**	**NbTi**
operating current	**(A)**	198/145	**145**	**198**
current density	**(A/mm^2)**		**123**	**141**
central field	**(T)**	**8.00**	**3.41**	**4.59**
max. field at wires	**(T)**		**8.41**	**5.52**
stored energy	**(MJ)**	**2.68**		
Hoop stress	**(MPa)**		**207**	**191**

Further, a cryogen-free superconducting magnet developed at the High Field Laboratory for Superconducting Materials as the world's first practical superconducting magnet with no use of cryogen [3] makes rapid progress, and is expected to offer an easy-operational high magnetic field for wide-range materials science. Until now, high field superconducting magnets generally need a wide room temperature bore from a viewpoint of practical applications, and this requirement resembles with the outer superconducting magnet of the hybrid magnet. A wide bore superconducting magnet made as compactly as possible should connect with a cryogen-free superconducting magnet requiring small heat loads and light weight. Fortunately, a great advantage of highly strengthened Nb_3Sn superconducting wires lies in offering a compact superconducting magnet.

In this article, a cryogen-free 8 T wide bore superconducting magnet employing high-strength Nb_3Sn wires is described. A cryogen-free 23 T hybrid magnet combined with a 15.5 T water-cooled resistive magnet is discussed.

II. CRYOGEN-FREE WIDE BORE SUPERCONDUCTING MAGNET

A. Compact Design of the Coil

The designed values of a cryogen-free wide bore superconducting magnet which will generate 8 T in a 360 mm room temperature bore are listed in Table I. The outer superconducting coil is wound with NbTi multifilamentary wires of 1.2 mm in diameter. High-strength Nb_3Sn multifilamentary wires with CuNb reinforcing stabilizer, CuNb/Nb_3Sn, are employed for the inner superconducting coil. Since CuNb/Nb_3Sn

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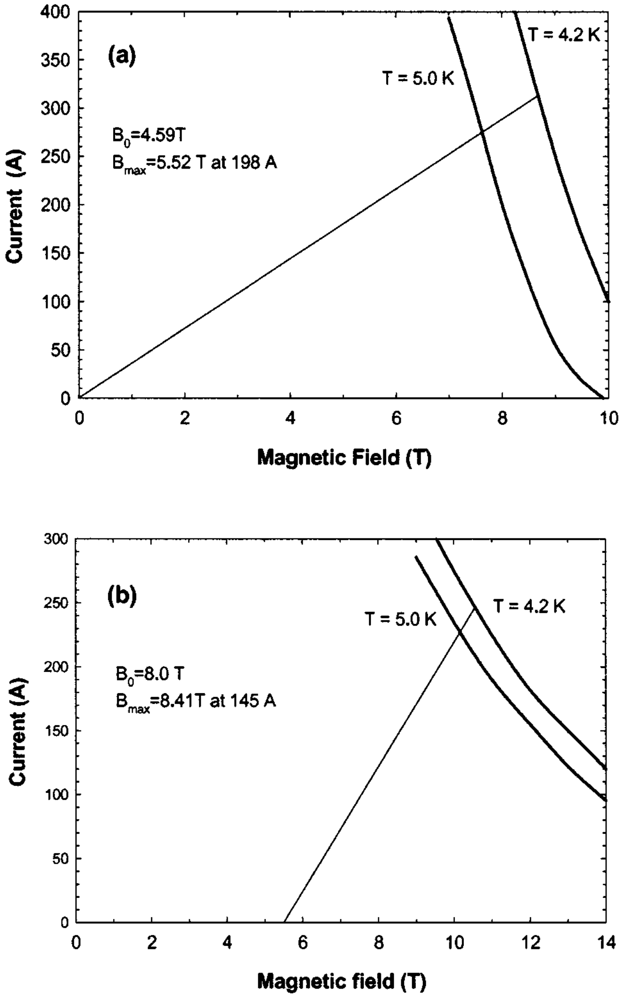

Fig. 1. Critical current properties and coil load lines for (a) the NbTi coil and (b) the CuNb/Nb_3Sn coil.

TABLE II
ESTIMATED HEAT LOADS OF A CRYOGEN-FREE WIDE BORE SUPERCONDUCTING MAGNET

		ramp rate of 0.3 A/s	hold at 198 A and 145 A
1st Stage			
Cu current leads	**(W)**	**20.1**	**20.1**
radiation	**(W)**	**50.5**	**50.5**
measuring wires	**(W)**	**0.40**	**0.40**
Joule heating	**(W)**	**2.4**	**2.4**
support pipes	**(W)**	**14.2**	**14.2**
TOTAL	**(W)**	**87.6**	**87.6**
2nd Stage			
Bi2212 current leads	**(W)**	**0.33**	**0.31**
radiation	**(W)**	**0.17**	**0.16**
measuring wires	**(W)**	**0.13**	**0.13**
Joule heating	**(W)**	**0.24**	**0.24**
support pipes	**(W)**	**0.40**	**0.40**
AC losses	**(W)**	**2.95**	**0**
TOTAL	**(W)**	**4.22**	**1.24**

wires exhibit about twice stronger yield stress than traditional Nb_3Sn wires using Cu stabilizer and stand with tensile stress of 300 MPa, the maximum electromagnetic stress level of 210 MPa is adopted as the inner CuNb/Nb_3Sn coil.

The outer NbTi coil and the inner CuNb/Nb_3Sn one are designed to generate central magnetic fields of 4.59 T at 198 A and 3.41 T at 145 A, respectively. Namely, this magnet has potential of a magnetic field generation of 8.0 T. When the cryogen-free wide bore superconducting magnet is operated as the hybrid magnet combined with a water-cooled resistive magnet, its generated magnetic field will be lowered to 7.5 T for the safety operation, because the resistive magnet can produce 15.5 T in a 52 mm room temperature bore. In order to carry out a compact magnet design, the dual power supplies system is also adopted. In addition, the method of dual power supplies has a technical merit suppressing a coil temperature rise during magnetic field sweep. This is because an inner coil with a small volume is energized by small operation current. Otherwise, AC-losses become larger due to a large volume coil operated with large current [4].

The magnetic stored energy of 2.7 MJ is absorbed by the cryogenic coil mass of 670 kg, when a coil quench happens to occur. The outer and inner coils are subdivided into 8 section layers each for the stored energy absorption through protection diodes. The induced voltages at divided layers are reduced less than 1.5 kV for the CuNb/Nb_3Sn coil and 2.0 kV for the NbTi coil, respectively.

B. Critical Currents of NbTi and CuNb/Nb_3Sn Wires and the Coil Load Line

The critical current characteristics of both NbTi and CuNb reinforced Nb_3Sn multifilamentary superconducting wires are shown in Fig. 1. The coil load lines are presented for the NbTi and CuNb/Nb_3Sn coils, together with the critical current-vs.-magnetic field curves. Critical currents in magnetic fields at 5.0 K are calculated from the flux pinning scaling, which is obtained by critical current data at 4.2 K. The cryogenic stability on the basis of liquid helium cooling cannot be applied for a cryogen-free superconducting magnet operated in vacuum, so that the critical current margin concept [5] is fundamentally used for the stable operation of a cryogen-free superconducting magnet. Here, we focus on the load ratio whose ratio means the operation current to the critical current. During magnetic field sweep, an operation current of 198 A for the outer NbTi coil corresponds to the load ratio of 72% at 5 K. When the coil is held at a constant magnetic field, the load ratio for the NbTi coil is reduced to 64%, due to the critical current enhancement at coil temperature below 4 K. Similarly, the operation current of 145 A for the inner CuNb/Nb_3Sn coil indicates the load ratios of 64% during ramping and 59% at the fixed current. The load ratio is further reduced in the hybrid magnet mode, because of the operation current of 124 A at 7.5 T.

C. Heat Load Evaluation

Table II lists the estimated heat loads in the first and the second stages of GM-cryocoolers for a cryogen-free wide bore superconducting magnet. AC losses were estimated under the condition of the simultaneous magnetic field sweep at 0.3 A/s for both inner and outer coils. One notices that thermal input through current leads into the second stage of GM-cryocoolers is sufficiently as small as 0.33 W at 198 A and 145 A in the dual

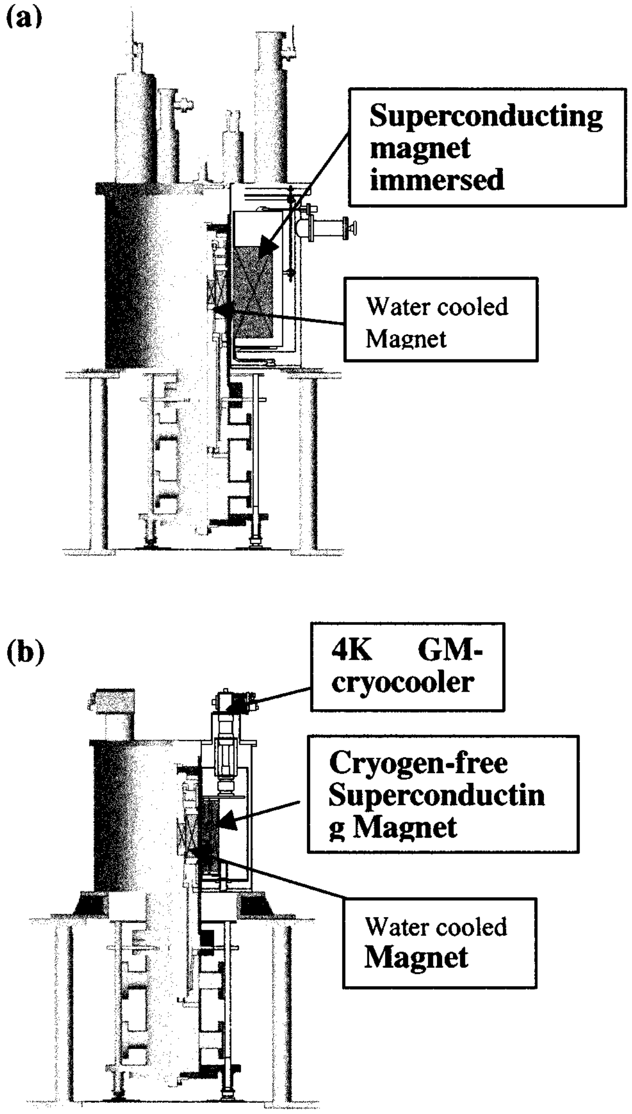

Fig. 2. Comparison of the system size between (a) the traditional 23 T hybrid magnet and (b) the cryogen-free 23 T hybrid magnet.

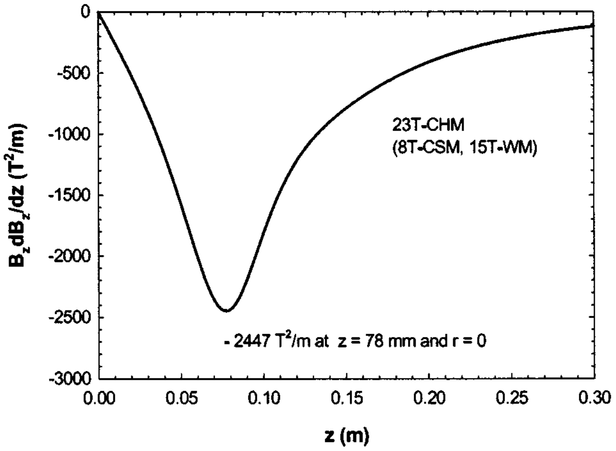

Fig. 3. Magnetic force as a function of the axial position from the center of the magnet in the cryogen-free 23 T hybrid magnet.

current supply system. This thermal insulation effect is responsible for the outstanding properties of high temperature ceramic superconductors. Since the total heat load into the second stage is estimated to be 1.24 W, two GM-cryocoolers can cover such the total heat load. As a result, the coil temperature below 4 K is expected sufficiently. However, four GM-cryocoolers were actually equipped with a wide bore superconducting magnet, in order to shorten the initial cool-down time below 100 h from room temperature.

III. CRYOGEN-FREE HYBRID MAGNET

A. Combination With a Water-Cooled Resistive Magnet

The size of the new cryogen-free 23 T hybrid magnet will become much smaller than that of the traditional 23 T hybrid magnet installed at Sendai. Fig. 2 shows the size comparison between the two. The huge Hoop stress works to a wide bore superconducting magnet as electromagnetic stress. In addition, the magnetically coupled interaction force has to be considered, in the case of the hybrid magnet operation. When a magnetic field center between a superconducting and a water-cooled resistive magnet is deviated, the magnetic interaction force appears. As a result, the deviation produces an attractive force, f_z, in the axial direction as a stable equilibrium, and a repulsive force, f_r, in the radial direction as an unstable equilibrium. The interaction force is absorbed by the supporting pipes of a cryostat. The force f_z and f_r are expressed in the form of

$$f_z = 4\pi t_z \int_{a1}^{a2} j(r) B_r(r, b) r \, dr, \tag{1}$$

$$f_r = 2\pi t_r \int_0^b dz \int_{a1}^{a2} j(r) \frac{\partial B_z(r, z)}{\partial r} r \, dr, \tag{2}$$

where t_z is a shifted difference along the axial direction, t_r along the radial direction, z axial distance, r radial distance, $j(r)$ a current density at r, $B_r(r, z)$ a magnetic field at r and z, and a_1, a_2, and b are coil parameters of a resistive magnet. When a magnetic field center of a resistive magnet is shifted by 1 mm, a superconducting magnet feels $f_z = 650$ kgf/mm or $f_r = 680$ kgf/mm. To stand with such a magnetic interaction force, six supporting FRP pipes with a size of $\phi 41 \times \phi 43.4 \times 177$ mm^3 are equipped inside the cryostat. These FRP pipes have the minimum allowable load of 4100 kgf as the shearing stress.

B. Magnetic Force

The diamagnetic material with the susceptibility of χ can be levitated by the magnetic force [6]. Since the magnetic force is given by

$$F = \frac{x}{\mu_0} B \frac{dB}{dz}, \tag{3}$$

the large levitation force requires not only a high magnetic field B but also a large magnetic field gradient dB/dz. We use the unit T^2/m as the value proportional to force. The hybrid magnet is appropriate to the large levitation force, because the water-cooled resistive magnet plays a role of a magnetic field gradient coil in high magnetic fields.

The cryogen-free 23 T hybrid magnet produces the magnetic force of 2450 T^2/m at the axial position of $z = 78$ mm above the center of the magnet, as shown in Fig. 3. This magnetic force is almost similar to the force of 2500 T^2/m by the old-type 23 T hybrid magnet. The force balanced with the gravitational force, which is given in the form of $F = g\mu_o/|\chi|$ using the gravity constant g, in some materials are 1370 T^2/m for water, 1990 T^2/m for SiO_2, and 2310 T^2/m for BK7 glass (mixture of SiO_2 and B_2O_5), for instance. Therefore, the cryogen-free 23 T hybrid magnet is available for the investigation of crystal growth in levitating aqueous solution and melt without crucible. The newly developed cryogen-free hybrid magnet will provide an easy-operational and a long-term experiment without supplying cryogen of liquid helium and liquid nitrogen.

IV. CONCLUSIONS

The cryogen-free 8 T superconducting magnet with a wide room temperature bore of 360 mm is being constructed at the High Field Laboratory for Superconducting Materials, IMR, Tohoku University. In order to make a compact wide bore superconducting magnet, the newly developed high-strength Nb_3Sn multifilamentary wires with CuNb reinforcing stabilizer are employed. The cryogen-free 23 T hybrid magnet consisting of the outer cryogen-free 7.5 T superconducting magnet and the inner 15.5 T water-cooled resistive magnet will be demonstrated for the first time.

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REFERENCES

[1] N. Kitamura, M. Makihara, M. Hamai, T. Sato, I. Mogi, S. Awaji, K. Watanabe, and M. Motokawa, “Containerless melting of glass by magnetic levitation method,” *Jpn. J. Appl. Phys.*, vol. 39, pp. L324–L326, 2000.

[2] K. Watanabe, M. Motokawa, T. Onodera, K. Noto, and T. Saito, “Advanced $(Nb,Ti)_3Sn$ superconducting wire with highly strengthened and good conductive CuNb composite stabilizer,” *Mater. Sci. Forum*, vol. 308–311, pp. 561–566, 1999.

[3] K. Watanabe, Y. Yamada, J. Sakuraba, F. Hata, C. K. Chong, T. Hasebe, and M. Ishihara, “$(Nb,Ti)_3Sn$ superconducting magnet operated at 11 K in vacuum using high-T_c $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ current leads,” *Jpn. J. Appl. Phys.*, vol. 32, pp. L488–L490, 1993.

[4] K. Watanabe, S. Awaji, M. Motokawa, S. Iwasaki, K. Goto, N. Sadakata, T. Saito, K. Watazawa, K. Jikihara, and J. Sakuraba, “Cryocooled large bore superconducting magnet for a hybrid magnet system employing highly strengthened $(Nb,Ti)_3Sn$ wires with CuNb stabilizer,” *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 440–443, 1999.

[5] Y. Iwasa, “A critical current margin design criterion for high performance magnet stability,” *Cryogenics*, vol. 19, pp. 705–714, 1979.

[6] M. Motokawa, K. Watanabe, S. Miura, S. Awaji, H. Nojiri, I. Mogi, S. Mitsudo, and T. Sakon, “Recent developments at the High Field Laboratory of Tohoku University,” *Phys. B*, vol. 246–247, pp. 360–363, 1998.