Cryocooled superconducting magnets for high magnetic fields at the HFLSM and future collaboration with the TML

K Watanabe, G Nishijima, S Awaji, K Koyama, K Takahashi, N Kobayashi and T Kiyoshi

1 High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
2 Tsukuba Magnet Laboratory, National Institute for Materials Science, Tsukuba 305-0003, Japan

E-mail: kwata@imr.tohoku.ac.jp

Abstract. A hybrid magnet needs a large amount of liquid helium for operation. In order to make an easy-to-operate hybrid magnet system, we constructed a cryocooled 28 T hybrid magnet, consisting of an outer cryocooled 10 T superconducting magnet and an inner traditional water-cooled 19 T resistive magnet. As a performance test, the cryocooled hybrid magnet generated 27.5 T in a 32 mm room temperature experimental bore.

As long as Nb3Sn superconducting wires are employed, the expected maximum high field generation in the cryocooled superconducting magnet will be 17 T at 5 K. We adopted the high temperature superconducting insert coil, employing Ag-sheathed Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ superconducting tape. In combination with the low temperature 16.5 T back-up coil with a 174 mm cold bore, the cryocooled high temperature superconducting magnet successfully generated the total central field of 18.1 T in a 52 mm room temperature bore.

As a next step, we start the collaboration with the National Institute for Materials Science for the new developmental works of a 30 T high temperature superconducting magnet and a 50 T-class hybrid magnet.

1. Introduction
The High Field Laboratory for Superconducting Materials (HFLSM) has demonstrated the activities for materials science and condensed matter physics, especially for superconducting and magnetic materials. These activities have been supported by the Institute for Materials Research, Tohoku University, which is the active world center of materials science. This advantage results in the success of the development of the first cryocooled superconducting magnet, especially the world’s first cryocooled hybrid magnet. Such cryocooled magnets surely offer long term stable and high quality static fields with much less time and less cost. It opens a new possibility for magneto-science.

In this report, the outstanding magnet technology related to the cryocooled superconducting magnets at the HFLSM is described, and the future collaboration with the Tsukuba Magnet Laboratory (TML) of National Institute for Materials Science is introduced.
2. Magnet technology highlights at the HFLSM

2.1. Cryocooled superconducting magnet development
The HFLSM succeeded in demonstrating a practical cryocooled superconducting magnet (CSM) without liquid helium as the first practical application of high temperature superconducting current leads in 1992 [1]. The world’s first practical cryocooled superconducting magnet, the 5T-CSM magnet, generated 4.6 T for an operating current of 465 A in a 38 mm room temperature experimental bore. Following the successful development of 5T-CSM, the HFLSM has focused on developing a functional, a wide-bore, and a high field cryocooled superconducting magnet [2]. A particularly important example is the use of X-ray diffraction for structure studies in high magnetic fields as shown in Fig. 1 [3]. Although X-ray diffraction experiments combined with high pressure, high temperature, or low temperatures have been carried out, it is much more difficult to assemble and operate an X-ray diffractometer in high magnetic fields. The cryocooled split-pair superconducting magnet (5T-CSSM) generates 5.0 T at the center of a 50 mm room temperature vertical bore, and has a 10 mm room temperature horizontal gap. The sample temperature can be varied under feedback control from 8 K to room temperature, using a GM-cryocooled sample cryostat inserted into a 50 mm room temperature bore. Using the X-ray diffractometer in high magnetic fields at low temperature, we are carrying out application-oriented research on magnetic-field-induced phase transformation [4].

2.2. Cryocooled 28 T hybrid magnet
The 30T hybrid magnet using liquid helium has been utilized to evaluate the critical current in fields

![Figure 1](image1.png)  
**Figure 1.** X-ray diffractometer in magnetic fields up to 5 T and at experimental temperatures ranging from 8 K to 300 K.

![Figure 2](image2.png)  
**Figure 2.** Outline of a 28 T cryocooled hybrid magnet consisting of an outer cryocooled 10 T superconducting magnet and an inner 19 T water-cooled resistive magnet.

![Figure 3](image3.png)  
**Figure 3.** 18 T cryocooled superconducting magnet using an Ag-sheathed Bi-2223 insert coil.
up to 30 T for advanced low temperature superconductors. Recently, the success of a container-less melting experiment is greatly attractive in the world [5]. The large magnetic force field of 4190 T/m is available. The hybrid magnet generating high fields over 30 T can provide the quite useful experimental conditions. In order to make an easy-to-operate hybrid magnet system, we newly constructed a cryocooled 28 T hybrid magnet (28T-CHM), consisting of an outer cryocooled 10 T superconducting magnet and an inner traditional water-cooled 19 T resistive magnet as shown in Fig. 2. 28T-CHM generated 27.5 T in a 32 mm room temperature experimental bore [6]. The wide bore cryocooled superconducting magnet is wound with Nb₃Sn wires reinforced by CuNbTi composite, which reveal strong mechanical properties of 300 MPa yield stress.

2.3. Cryocooled 18 T high temperature superconducting magnet
The high field cryocooled superconducting magnet developed at the HFLSM made rapid progress. This progress of the high magnetic field generation by a practical cryocooled superconducting magnet strongly depends on the development of regenerator materials. Although the world’s first practical CSM was cooled by a GM-cryocooler with a refrigeration power of 0.5 W at 11 K using a Pb regenerator material, the high field cryocooled 15.1 T superconducting magnet uses 4 K GM-cryocoolers with the magnetic regenerator material of HoCu₂, which has an excellent refrigeration power of 1.0 W at 4.2 K. The operating temperature of the cryocooled superconducting magnet is limited at around 4-5 K, when the superconducting magnet is energized at the practical ramp rate. As long as Nb₃Sn superconducting wires are employed, the expected high field generation in the cryocooled superconducting magnet will be 16-17 T. Therefore, we adopted the high temperature superconducting insert coil, employing Ag-sheathed Bi₂Sr₂Ca₂Cu₃O₁₀ superconducting tape.

The 20 T-class superconducting magnet has to stand an induced electromagnetic stress of 160 MPa, which is related to the magnetic energy per a unit volume in the form of E = B²/2μ₀. The silver based alloy Bi-system high temperature superconducting tape has the similar yield stress. In order to ensure the mechanical properties, the co-winding technique with stainless steel tape will be attempted. The coil installed in a vacuum is conductively cooled by means of the JT/GM-cryocooler, in order to improve the refrigeration ability with a low cost as shown in Fig. 3. The low temperature back-up coil will generate 16.5 T in a 174 mm cold bore, and the cryocooled high temperature superconducting magnet (18T-CSM) generated 18.1 T in a 52 mm room temperature experimental bore [7].

3. Ongoing and near future projects conducted by the HFLSM and the TML

3.1. 30 T high temperature superconducting magnet
For a future high field superconducting magnet over 30 T, the HFLSM and the TML start to investigate a new reinforcing technique against a huge hoop stress of 360 MPa at 30 T. One of the good candidates to reinforce a high temperature superconducting insert is to employ the scheme of the Hastelloy tape co-winding technique for double pancake coils. In this method, we demonstrated the critical current without degradation up to a hoop strain of 0.3 % at 270 MPa for Ag-sheathed Bi₂Sr₂Ca₂Cu₃O₁₀ superconducting tape [8]. The primitive design to generate 27 T in a 52 mm experimental cold bore is attempted in a coil configuration composed of 12 T Bi₂Sr₂Ca₂Cu₃O₁₀, 6 T Nb₃Sn, and 9 T NbTi coils. The designed double pancake coil technique will be extended similarly to a further strong 30 T high temperature superconducting magnet.

In addition, we have to develop a precise magnetic field generation for an NMR magnet. This results in not a tape shape but a round shape wire. In this process, a W&R method is adopted to make a coil using a round Ag-sheathed Bi₂Sr₂Ca₂Cu₃O₁₀ wire. A problem encountered with the W&R process is a difficult insulation technique. The glass cloth insulation used for the Nb₃Sn heat-treatment process is not available for a Bi₂Sr₂Ca₂Cu₃O₁₀ formation reaction in an oxygen atmosphere. We intended to make electric insulation cloth knitted into a braid tube covering a wire surface for a W&R processed Ag/Bi₂Sr₂Ca₂Cu₃O₁₀ superconducting magnet [9]. It is well-known that Hastelloy X (Hx) materials reveal good tolerance of oxidization in high temperature heat-treatment in O₂ gas. As the first step to develop a knitting method
employing 50 μm diameter Hx filaments without pre-oxidization, we adopted the knitting density with 1.4 mm pitch. It was a good condition to obtain the Hx filament braid cloth. The heat-treatment is carried out after the knitting process using a short length wire, and at the same time the surface oxidization of Hx filaments with good electric insulation between wires can be formed. To push this W&R process forward, a round Ag-sheathed Bi2212 wire reinforced internally should be developed.

3.2. 50 T-class hybrid magnet consisting of a 22 T superconducting outsert
As the next phase hybrid magnet, the HFLSM and the TML are planning to construct a 50 T-class hybrid magnet consisting of a 22 T superconducting outsert. In order to develop a wide bore 22 T superconducting magnet with a 400 mm room temperature bore for the combination of a resistive insert, new high strength Nb$_3$Sn wires, which stand a large hoop stress over 500 MPa, are inevitably required for magnet design. So far, we found that the prebending strain treatment of 0.8 % enhances the critical current without any degradation for a bronze route Nb$_3$Sn reinforced with CuNb composite [10]. If we concentrate on strand cables employing the prebent Nb$_3$Sn wires and stainless steel wires, it is expected that the primitive design of high strength Nb$_3$Sn strand cables listed in Table 1 may be possible for practical use. We can design the 22 T superconducting outsert with a 440 mm cold bore, employing the high strength Nb$_3$Sn strand cables.

Acknowledgments
The cooperative research subjects of the highly strengthened Nb$_3$Sn wire with Furukawa Electric Co. Ltd., the cryocooled 28 T hybrid magnet with Sumitomo Heavy Industries Ltd., and the cryocooled 18 T superconducting magnet with Toshiba Co. are greatly acknowledged.

References
[1] Watanabe K, Yamada Y, Sakuraba J, Hata F, Chong C K, Hasebe T and Ishihara M 1993 Jpn. J. Appl. Phys. 32 L488
[2] Watanabe K and Awaji S 2003 J. Low Temp. Phys. 133 17
[3] Watanabe K, Watanabe Y, Awaji S, Fujiwara M, Kobayashi N and Hasebe T 1998 Adv. Cryo. Eng. 44 747
[4] Koyama K, Sakai M, Kanomata T and Watanabe K 2004 Jpn. J. Appl. Phys. 43 8036
[5] Kitamura N, Makihara M, Hamai M, Sato T, Mogi I, Awaji S, Watanabe K and Motokawa M 2000 Jpn. J. Appl. Phys. 39 L324
[6] Watanabe K, Nishijima G, Awaji S, Takahashi K, Koyama K, Kobayashi N, Ishizuka M, Itou T, Tsurudome T and Sakuraba J 2006 IEEE Trans. Appl. Supercond. in press
[7] Nishijima G, Awaji S, Hanai S and Watanabe K 2006 Fusion Eng. Des. in press
[8] Wakuda T, Okada M, Awaji S and Watanabe K 2001 Physica C 357-360 1293
[9] Watanabe K, Nishijima G, Awaji S, Hikichi Y and Hasegawa T 2006 Adv. Cryo. Eng. 52 704
[10] Watanabe K, Awaji S, Oguro H, Nishijima G, Miyoshi K and Meguro S 2005 IEEE Trans. Appl. Supercond. 15 3564

| Table 1. Cable configuration and stress limit at $\varepsilon = 0.4$ % under the condition of $I_c = 1000$ A at 2.0 K and at the maximum field $B_m$ |
|---|---|---|
| strand cable configuration | stress limit [MPa] | $B_m$ (T) |
| $8 \times (\phi 1.46\text{Nb}_3\text{Sn})+1\times \text{SUS}$ | 364 | 20.9 |
| $4 \times (\phi 1.18\text{Nb}_3\text{Sn})+5\times \text{SUS}$ | 582 | 16.2 |
| $3 \times (\phi 1.73\text{Nb}_3\text{Sn})+4\times \text{SUS}$ | 552 | 18.5 |