Design of a Cryocooler-Cooled Large Bore Superconducting Magnet for a 30 T Hybrid Magnet

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***Abstract*—We are now developing a 30 T hybrid magnet utilizing a cryocooler-cooled superconducting magnet wound with highly strengthened $(Nb, Ti)_3Sn$. Diameter of the room temperature bore of the superconducting magnet is 360 mm and it generates 11.1 T. Water cooled resistive insert magnet generates 18.9 T, thus the hybrid magnet generates a central field of 30.0 T. The $(Nb, Ti)_3Sn$ multifilamentary wires are strengthened by Cu/NbTi composite which volume ratio in conductor is about 35%. The reinforcing Cu/NbTi composite changes to CuTi intermetallic compounds during heat treatment for reaction of $(Nb, Ti)_3Sn$ phase formation. The Nb_3Sn coil with inner diameter of 400 mm will be fabricated by wind and react method with Cu/NbTi reinforced $(Nb, Ti)_3Sn$ wires. The innermost section of Nb_3Sn coil is wound with a wire which diameter is 1.85 mm and next second section is wound with a wire diameter of 1.8 mm. The Nb_3Sn coil is operated at 303 A and generates 5.8 T. The NbTi coil is wound with NbTi wires of 2.0 mm and 1.6 mm diameters. The NbTi coil generates 5.3 T at an operating current of 350 A. The maximum hoop stress is under 220 MPa for Nb_3Sn coil and 200 MPa for NbTi coil.**

***Index Terms*—Cryocooler-cooled superconducting magnet, Cu/NbTi reinforced $(Nb, Ti)_3Sn$, high magnetic field, hybrid magnet.**

I. Introduction

Cryocooler-cooled superconducting magnet have been developed as the world's first success using Bi-based superconducting oxide current leads with small Gifford McMahon (GM) cryocoolers in 1992 [1]. This first demonstration of the 4 T cryocooler-cooled $(Nb, Ti)_3Sn$ magnet was operated at the maximum current of 400 A and in the temperature range of above 10 K. Up to now, progress on cryocooler technology enables us to construct high field cryocooler-cooled superconducting magnets which employ both $(Nb, Ti)_3Sn$ and NbTi wires operated below 5 K. Practically, a 15 T cryocooler-cooled superconducting magnet has developed in 1998 using two GM cryocoolers with cooling capacity of 1.0 W at 4.2 K [2].

Further, an 8 T cryocooler-cooled large bore super-conducting magnet for a 23 T hybrid magnet has been developed employing highly strengthened superconducting wires to overcome a huge electromagnetic stress [3]. Following the above mentioned studies, the development of a 11 T class cryocooler-cooled large bore superconducting magnet for a 30 T hybrid magnet with has been started. In this paper, we report a design of a cryocooler-cooled large bore super-conducting magnet for a 30 T hybrid magnet.

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TABLE I
Specifications of Superconducting Wires for Inner Sections

	Type A	Type B
Superconductor	(Nb,Ti)$_3$Sn	(Nb,Ti)$_3$Sn
Reinforcement material	Cu/NbTi	Cu/NbTi
wire diameter[mm]	1.85	1.80
Composition ratio		
Cu stabilizer[%]	35	35
Cu/NbTi reinforcement[%]	28	33
Nb+bronz[%]	37	32
Filament diameter[μm]	3.5	3.5
Number of filaments	25,536	19,969
Twist pitch[mm]	50	50
Critical current		
at 12 T, 4.2 K[A]	> 465	> 393
at 14 T, 4.2 K[A]	> 330	> 278
Insulation material	E-glass	E-glass
Insulation thickness[mm]	0.075	0.075
0.2 % proof stress[MPa]	> 230	> 237

II. Superconducting Magnet Design

A. Conductor Design

The superconducting magnet consists of two grading coils and utilizes two types of superconducting wires. The outer coil will be wound with the conventional NbTi multi-filamentary wires. The inner coil will be wound with high-strength Nb_3Sn multi-filamentary wires which contains a Cu/NbTi reinforcement, which were just developed for a large bore high field magnets, in order to overcome a huge hoop stress in the coil windings. The remarkable enhancement of 0.2% proof stress in this wire has been obtained and it reaches over 260 MPa [4].

The specifications of Cu/NbTi reinforced $(Nb, Ti)_3Sn$ wires for our magnet are listed in Table I. The wire with diameter of 1.85 mm, Type A, is designed for inner most coil section of the magnet. Type B with diameter of 1.80 mm for the second inner section has much reinforcement volume and less superconducting filaments number.

The temperature dependence of upper critical field B_{c2} was measured at 13 T and 15 T, respectively. Fig. 1 shows the experimental data for Cu/NbTi/$(Nb, Ti)_3Sn$ wire and the data fitted for traditional bronze-route $(Nb, Ti)_3Sn$ wire. It is predicted that reinforced $(Nb, Ti)_3Sn$ wire has relatively large prestrain after

TABLE II
COIL PARAMETERS OF A CRYOCOOLER-COOLED LARGE BORE SUPERCONDUCTING MAGNET

	Section A	Section B	Section C	Section D
superconductor	Cu/NbTi/(Nb,Ti)$_3$Sn	Cu/NbTi/(Nb,Ti)$_3$Sn	NbTi	NbTi
wire diameter [mm]	1.85	1.80	2.00	1.60
coil inner diameter [mm]	398	493	606	694
coil outer diameter [mm]	475	576	664	752
coil height [mm]	400	450	500	550
operating current [A]	303	303	350	350
overall current density [A/mm^2]	85.5	90.0	93.2	143.0
central field [T]	11.1(2.8)	8.3(3.0)	5.3(2.1)	3.2
maximum field [T]	12.4	9.7	6.5	4.1
critical temperature [K]	7.5	8.0	6.0	7.0
wire length [km]	6.0	9.2	7.7	14.9
wire mass [kg]	146	213	220	272
wire volume [cm^3]	16200	23600	24400	30200
hoop stress [MPa]	210	215	183	201

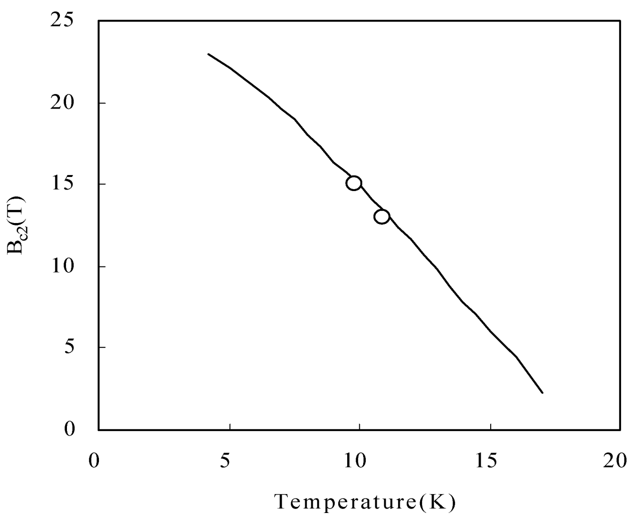

Fig. 1. Upper critical field as a function of temperature for Cu/NbTi reinforced (Nb, Ti)$_3$Sn wires. Open circles denote measurement result for the wire and solid line shows a fitted data.

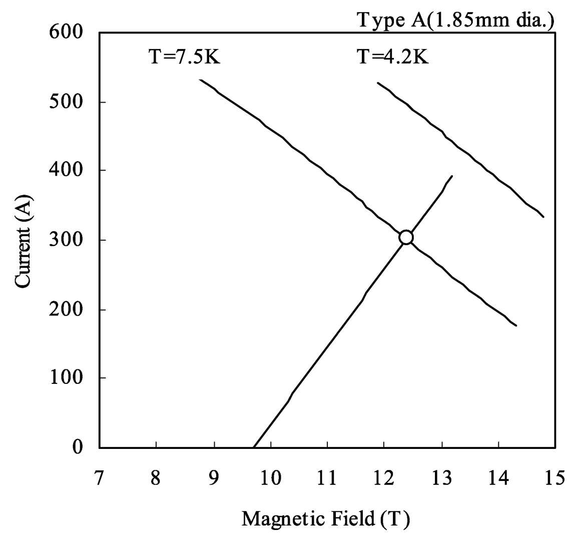

Fig. 2. Critical current as a function of magnetic field and coil load line for coil A using Cu/NbTi/(Nb, Ti)$_3$Sn wire with diameter of 1.85 mm. An open circle denotes an operating point for $B_o = 11.1$ T and $B_{max} = 12.4$ T at 303 A. The critical temperature of full energized coil A is said to be about 6.5 K from this plot.

heat treatment and small B_{c2} compared to traditional Cu stabilizing wires [5]. The critical current at various temperature is estimated based on the B_{c2} curve as shown in this figure.

B. Coil Design

The designed parameters of the cryocooler-cooled large bore superconducting magnet for a 30 T hybrid magnet are listed in Table II. The magnet which consists of four coil sections will generate 11.1 T in a 360 mm room temperature bore.

Highly strengthened inner coils which generate a central field of 5.8 T are inserted in a back up NbTi outer coils with central field of 5.3 T. The inner coil consists of two sections, i.e., section A with wires of 1.85 mm in diameter and section B with 1.80 mm in diameter. Fig. 2 shows the critical current properties of type A wire at 7.5 K calculated by the scaling law of global pinning force from the 4.2 K. The load line of the coil section A is also plotted in the figure together with an operating point for $B_{max} = 12.4$ T at 303 A as an open circle. The T_c (critical temperature) of full energized coil A is estimated to be around 7.5 K. Fig. 3 shows the critical current properties of type B wire at 8.0 K calculated by the scaling law of global pinning force from the 4.2 K data. The load line of the coil section B is also plotted in the figure together with an operating point for

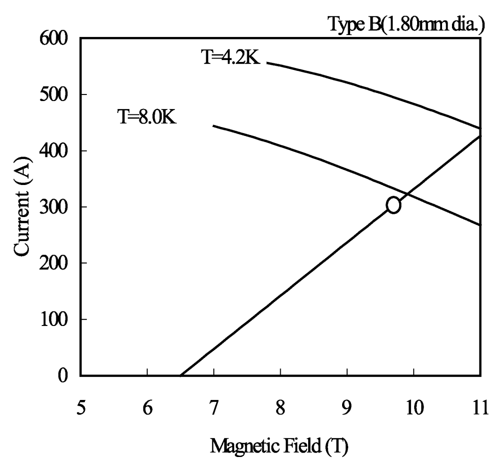

Fig. 3. Critical current as a function of magnetic field and coil load line for coil B using Cu/NbTi/(Nb, Ti)$_3$Sn wire with diameter of 1.80 mm. An open circle denotes an operating point for $B_o = 8.27$ T and $B_{max} = 9.70$ T at 303 A. The critical temperature of full energized coil A is said to be about 7.5 K from this plot.

TABLE III
ESTIMATION RESULTS OF HEAT LOAD OF A CRYOCOOLER-COOLED LARGE BORE SUPERCONDUCTING MAGNET

	No operating current	Full energized at full ramp rate
Inner $(Nb,Ti)_3Sn$ coils		
Operating current [A]	0	303
Ramp rate [A/sec.]	0	0.175
Outer NbTi coils		
Operating current [A]	0	350
Ramp rate [A/sec.]	0	0.184
1^{st} stages heat load		
Cu current leads [W]	21.3	38.2
Radiation [W]	26.0	26.0
Measuring wires [W]	0.4	0.4
Joule heating [W]	0	8.5
Support structures [W]	6.3	6.3
TOTAL [W]	54.0	79.5
2^{nd} stages heat load		
Bi-2223 current leads [W]	0.18	0.18
Radiation [W]	0.05	0.05
Measuring wires [W]	0.20	0.20
Joule heating [W]	0	0.86
Support structures [W]	0.46	0.46
AC losses		
$(Nb,Ti)_3Sn$ coils [W]	0	0.30
NbTi coils [W]	0	0.75
heat conductor (copper) [W]	0	1.70
TOTAL [W]	0.89	4.5

$B_{max} = 9.7$ T at 303 A as an open circle. The T_c of full energized coil B is estimated to be around 8.0 K.

The outer NbTi coil is subdivided into two sections, section C with wires of 2.00 mm in diameter and section D with wires of 1.60 mm in diameter. The NbTi coils generate a central field of 3.2 T for section D and 2.1 T for section C with the same operating current of 350 A. The estimated values of T_c at an operating current of 350 A are 6.0 K for section C and 7.0 K for section D, respectively. The T_c of the magnet is equal to the T_c of the coil C which is the lowest value of T_c.

The inductance of inner Nb_3Sn coil section with an operating current of 303 A is calculated to be 55 H including a mutual inductance against the outer NbTi coils. The total inductance of NbTi coil is 89 H. Then the total stored energy of the magnet is about 8 MJ. These coils are subdivided electrically and shunt with protection diodes circuit in order to reduce inner voltage inside coil windings below 1.0 kV for Nb_3Sn coils and 1.5 kV for NbTi coils.

C. Cryogenic Design

The superconducting coils are cooled down to below 4 K by the second stages of GM-cryocoolers through solid state thermal conduction in vacuum atmosphere. The GM-cryocoolers have two cooling stages. The first stage has cooling power of 35 W at 50 K and second one has 1.5 W at 4.2 K. The estimation results of heat loads to the first and second stages of GM-cryocoolers are listed in Table III. In the case of four GM-cryocoolers are employed, heat load to each cryocooler is calculated to be about 1.1 W for second stage and about 20 W for first stage. The temperature of each cooling stage is estimated using standard load map of cooling capacities as shown in Fig. 4. As a result, the stage temperature is estimated to be 4.0 K for the second stage and 36 K for the first stage.

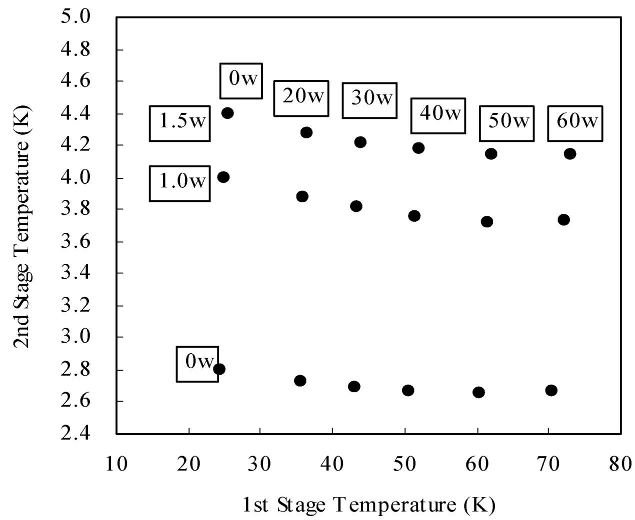

Fig. 4. A standard load map of cooling capacities for the GM-cryocooler with nominal cooling capacity of 1.5 W at 4.2 K. The tested heat load range from 0 W to 60 W for first stage and from 0.0 W to 1.5 W for second stage, respectively.

The margin of critical temperature of the coils to the cooling temperature of the second stages are over 2.0 K and is seems to be enough. But, an actual temperature inside coil windings is determined by the temperature gradient in the magnet which depends on the thermal conduction properties and the quantity of heat generation. Optimizing thermal conduction properties, it must be considered following points. Thermal conductivity of copper at low temperature depends on the magnitude of magnetic flux density especially over 8 T. In addition, larger thermal conduction path is better for thermal conductivity, but, it results in greater eddy current heating and higher coil temperature. Therefore, an optimum design for thermal conducting elements is determined by trade-off between heat generation and thermal conduction. As a result of above studies, maximum coil temperature is estimated to be 5.5 K which is 0.5 K below the lowest critical temperature of the coils.

III. CONCLUSION

An 11 T class cryocooler-cooled superconducting magnet with a large room temperature bore of 360 mm for a 30 T hybrid magnet is being constructed. The inner coils is going to be fabricated by the wind-and-react and vacuum impregnated methods employing highly strengthened $(Nb,Ti)_3Sn$ wires reinforced by Cu/NbTi composite.

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REFERENCES

[1] K. Watanabe, Y. Yamada, J. Sakuraba, F. Hata, C. K. Chong, T. Hasebe, and M. Ishihara, "$(Nb,Ti)_3Sn$ superconducting magnet operated 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.

[2] K. Watanabe, S. Awaji, M. Motokawa, Y. Mikami, J. Sakuraba, and K. Watazawa, “15 T cryocooler-cooled Nb_3Sn superconducting magnet with a 52 mm room temperature bore,” *Jpn. J. Appl. Phys.*, vol. 37, pp. L1148–L1150, 1998.
[3] K. Watanabe, S. Awaji, K. Takahashi, G. Nishijima, M. Motokawa, K. Jikihara, M. Ishizuka, and J. Sakuraba, “First performance test of the cryogenfree hybrid magnet,” *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, pp. 1632–1635, June 2003.
[4] K. Miyoshi, K. Wada, S. Meguro, G. Nishijima, S. Awaji, and K. Watanabe, Development of High Strength Nb_3Sn Conductor. this conference.
[5] K. Watanabe, S. Awaji, M. Motokawa, S. Iwasaki, K. Goto, N. Sadakata, T. Saito, K. Watazawa, K. Jikihara, and J. Sakuraba, “Cryocooler-cooled 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, no. 2, pp. 440–443, June 1999.