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Design of an 8 MW Water-Cooled Magnet for a 35 T Hybrid Magnet at theHFLSM

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***Abstract*—A new water-cooled poly Bitter magnet for a hybrid magnet was designed under the fully utilization of the electric power source of 8 MW and the cooling system installed in the High Field Laboratory for Superconducting Materials, Tohoku University. The magnet consists of four axial water-cooled Bitter coils, which are electrically connected in series and all of cooling water flows from the bottom to upper side of coils. The designed poly Bitter magnet will produce 22.8 T by 7.5 MW in the room temperature bore of 16 mm and 34.3 T as a hybrid magnet with a backup field of 11.5 T. A magnetic force field, $B(\partial B/\partial z)$, reaches to approximately $-11,100$ T^2/m at the central field of 34.3 T, which is very large enough to levitate semiconductors such as silicon or germanium.**

***Index Terms*—Bitter coil, high magnetic field, hybrid magnet, water-cooled magnet.**

I. Introduction

THE High Field Laboratory for Superconducting Materials, Tohoku University (HFLSM) succeeded in producing 31.1 T using a hybrid magnet in 1986 [1], which was the highest field in the world at that time. In 2000, a hybrid magnet at the NHMFL in the USA produced 45.1 T [2]. After that, most of the high field facilities in the world attempt the generation of over 40 T by hybrid magnets [3], [4]. The generation of fields over 40 T is becoming the word standard in the high field facilities today. We also attempt the generation of a higher magnetic field than 31.1 T at the HFLSM.

The progress of highest field by using hybrid magnets is partly due to developments of a superconducting outsert magnet. Improvement in mechanical properties of superconducting wires enables to make a high-field and wide-bore superconducting magnet for an outsert magnet of hybrid magnets. Another approach to highest fields is the employment of a large electric power for a water-cooled insert magnet. Facilities that intend to produce over 40 T employ an over 20 MW class electric power system. As well known, the strength of magnetic field produced by a water-cooled magnet is proportional to the square root of the dissipated electric power in the magnet. At the HFLSM, one of the water-cooled magnets produces a field up to 19 T in a space of 32 mm room temperature bore by a 7.2 MW dissipated electric power, and 30 T is usually produced as the hybrid magnet in an 11.5 T backup field using a superconducting outsert magnet. If a stronger electric power of 20 MW is available, the field of 32 T can be produced by the water-cooled magnet, and 44 T will be obtained in a 12 T backup field using a full ability of the outsert. However, it is difficult to build a new 20 MW or even a 16 MW electric power plant, twice of the present system, at the HFLSM due to the budget problem. Therefore we have to consider and design a 35–40 T class magnet with even a small bore by use of an existing 8 MW electric power source and cooling system. As the first step, we designed a water-cooled magnet for an 8 MW and 35 T hybrid magnet under an 11.5 T backup field by the existing superconducting outsert magnet. If we use a newly developed cryogen-free 11 T superconducting magnet [5], we may realize an 8 MW and 34 T cryogen-free hybrid magnet.

II. Design of a Small-Bore Water-Cooled Magnet

A small-bore water-cooled magnet has been designed on the basis of the previous report by Miura *et al.* [6]. In this report, it aimed to produce the field of 24 T by the designed water-cooled poly Bitter magnet, and a 40 T field will be provided as the hybrid mode in a 16 T backup field by a new compact superconducting magnet [7]. This water-cooled magnet, however, was designed on the assumption of use of a new outer coil case for a water-cooled magnet, which is different form an existing coil case in an available size of the outermost diameter of a coil. In a present plan, we use an existing outer coil case as well as an existing electric power plant and cooling system in order to reduce costs of the construction. Therefore, the outermost diameter of a water-cooled magnet must be reduced less than the previous design of 320 mm. Consequently, the outermost diameter of a coil is limited to 300 mm due to the inner diameter of the coil case.

We adopt the four Bitter coil configuration in the same way as the previous one, because the basic concept and design is good and sufficient for our present plan. Of course, in order to make a high-power water-cooled magnet for a hybrid magnet over 30 T, the design of a polyhelix coil is probably easier than that of a Bitter coil from a viewpoint of electromagnetic stress. The structure of the polyhelix coil, however, is more complex than that of the Bitter coil and not easier to repair when coils are broken than the Bitter coils. Furthermore, Cu-Ag alloys developed by Sakai *et al.* [8] which have very high yield strength and high electrical conductivity enable us to design the high-field Bitter coil.

In order to realize an 8 MW and 35 T compact hybrid magnet, we have started on designing the new coils based on the previous ones. At first the diameter of each coil is roughly determined and is approached to optimum shape during the computation in consideration of the length of coils, the thickness of the conductor disks, the cooling holes distribution of each Bitter disk and so on. The thickness and the cooling holes distribution of

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TABLE I
THE PARAMETERS OF THE DESIGNED POLY BITTER COIL FOR 35 T HYBRID MAGNET

	No. 1 coil (Innermost)	No. 2 coil	No. 3 coil	No.4 coil (Outermost)	Total
Inner diameter (mm)	20.0	69.3	131.6	207.4	
Outer diameter (mm)	65.5	127.6	203.4	300.0	
Coil height (mm)	64.4	78.4	129.5	216.0	
Thickness of disk (mm)	0.9	0.9	1.2	1.3	
Number of disks	69	84	105	162	
Thickness of insulator (mm)	0.1	0.1	0.1	0.1	
Number of turns [a]	21	26	32	50	
Electric current (kA)	23.0	23.0	23.0	23.0	23.0
Across voltage (V)	43.6	67.0	84.0	130.5	325.1
Dissipated power (MW)	1.00	1.54	1.93	3.00	7.47
Flow rate of cooling water (m^3/h)	77.9	85.0	69.4	110.3	342.6
Generated field (T)	8.025	6.015	4.457	4.329	22.826
Coil constant (T/kA)	0.349	0.262	0.194	0.188	0.992
Resistance of coil (mΩ)	1.90	2.91	3.65	5.67	14.13
Hoop stress (MPa)	594	556	408	365	

[a] three disks per a turn; see text

each Bitter disk are determined so as to give the uniform temperature rise taking account of the mechanical and thermal limitations. The temperature rise is determined by the balance of Joule heating and cooling by water. The distribution of cooling holes in a Bitter disk is determined by Clement's equation. The detailed calculation method was described in the previous report [9].

The numerical values and other designed characteristics of the coils are listed in Table I. Number of the coil is named in order from inner to outer one. The innermost diameter of the coil is 20 mm and the outermost diameter of the coil is 300 mm. A room temperature bore of the magnet is 16 mm and an experimental bore of 8 mm will be available in liquid helium. The liquid helium bore is small compared with a standard cryostat for the current hybrid magnets. For experiments using a pulse magnet, however, most of measurements are performed in almost same liquid helium bore size or smaller than 8 mm. Therefore, the physical property measurements such as magnetization or electrical resistivity measurements at low temperature will be carried out by using the newly designed magnet.

The electric current through the coil is 23 kA and the total across voltage of coils is 325 V. The dissipated electric power is 7.5 MW. The coil constant is 0.992 T/kA as a whole. When the inlet cooling water temperature is 10°C and the flow rate of cooling water is 343 m^3/h, the temperature of the conductor contacting to water is less than 81°C. The maximum hoop stress is 594 MPa which occurs in the innermost coil. Therefore, we use Cu-24 wt.% Ag alloy plates as the conductor of the Bitter disks. For the no. 1 and no. 2 coils, Cu-Ag plate with the electrical conductivity of 80%IACS and the yield strength of 750 MPa will be used. It has enough margins of 20% for the hoop stress. Cu-Ag plates with 85%IACS and 550 MPa, and 90%IACS and 500 MPa will be used for the no. 3 and no. 4 coil respectively.

Each coil is composed of a stack of disks and two kind of fan-shaped insulator plates with angle of 120° and 90°. The stack is piled with a conductor disk, 120° insulator plate, second disk, 120° plate, third disk, 90° plate and next disk in that order. Hence, three conductor disks compose a single turn of a coil [10].

Fig. 1 shows the schematic illustration of the four Bitter disks. Slender slots are adopted at the inner region of the second outer coil and at the whole region of two inner coils to obtain higher cooling efficiency and reduction of hoop stress [11]. Each bolt hole is encircled with four small semicircular holes for cooling channels. Therefore the Bitter disks can be fixed and cooled by using such bolt holes [12]. The innermost coil, no. 1 coil, is fixed with the next outer no. 2 coil by flanges, because no. 1 coil has no bolt holes due to the narrowness of the disk. Square notches at the outer diameter of the no. 1 coil and the inner of the no. 2 represent holes for guide rods to keep a phase between no. 1 and no. 2 coil during stacking them. The shape, however, has not been optimized to reduce the current density and the stress concentration around the notches. It will be optimized by Finite Element Model (FEM) analysis. Fig. 2 illustrates the cross section of the designed poly Bitter coils. The effective coil height and the diameter of the coil are shown in the figure. Four coils are electrically connected in series. The cooling water flows from the bottom to the top in whole coils.

Fig. 3 shows the calculated field distribution of the newly designed water-cooled magnet and its hybrid mode. For hybrid mode, the backup field of the superconducting magnet is 11.5 T and total field will reach up to 34.3 T at the center of the magnet. The field homogeneity of the hybrid magnet is estimated to be less than 0.3% in the volume of a 10 mm diameter sphere.

The maximum field of the present design is slight smaller than our target field of 35 T. The first target, however, will be achieved by more optimization with FEM analysis of the current density and the stress in each conductor disk.

III. MAGNETIC FORCE FIELD

In recent years, magnetic levitation of diamagnetic materials has received much attention as a new technique for materials processing [13]–[15]. The magnetic force, F_{mag}, acting on the unit mass of the materials is given by

$$F_{mag} = \frac{\chi_g}{\mu_0} B \frac{\partial B}{\partial z}, \tag{1}$$

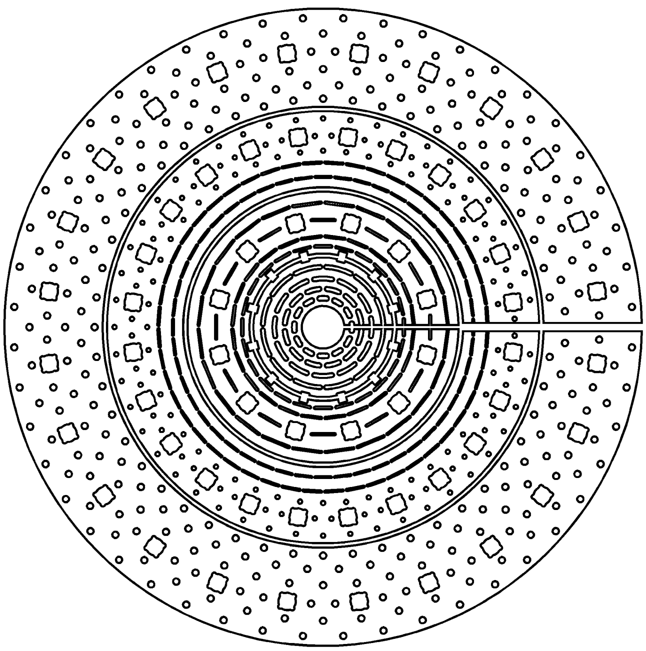

Fig. 1. Schematic illustration of the four Bitter disks in a coaxial position. Large square-like holes are bolt holes for stacking the disks.

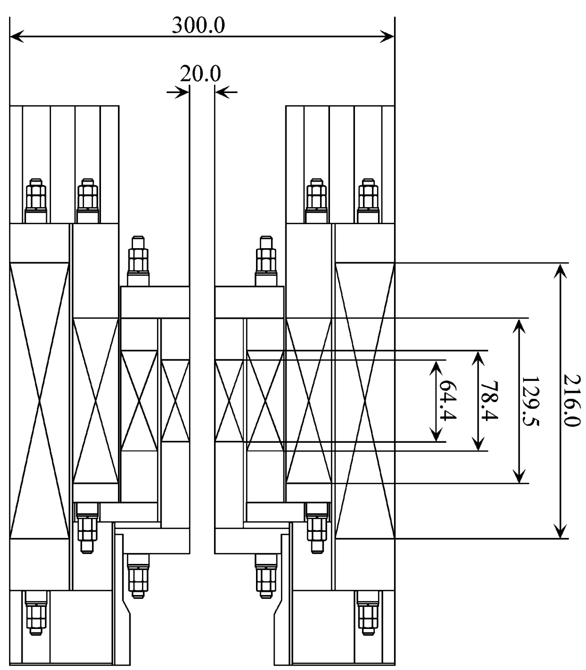

Fig. 2. Schematic configuration of the poly Bitter magnet consisting of four Bitter coils.

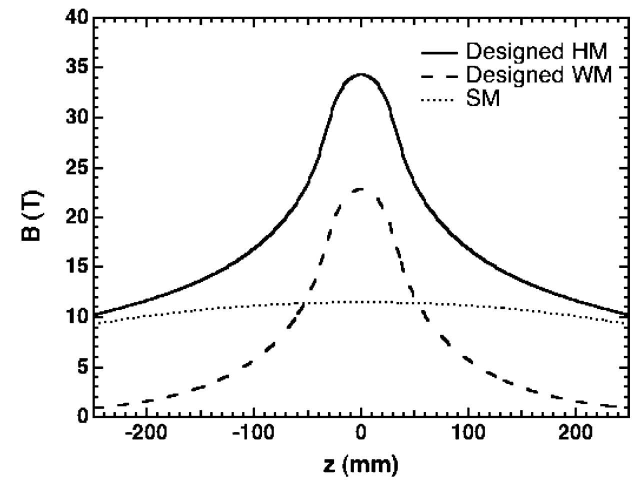

Fig. 3. Calculated field distribution of the poly Bitter magnet (broken line) along z-axis, a hybrid mode (solid line) in a backup field of 11.5 T by the existing superconducting magnet (dotted line).

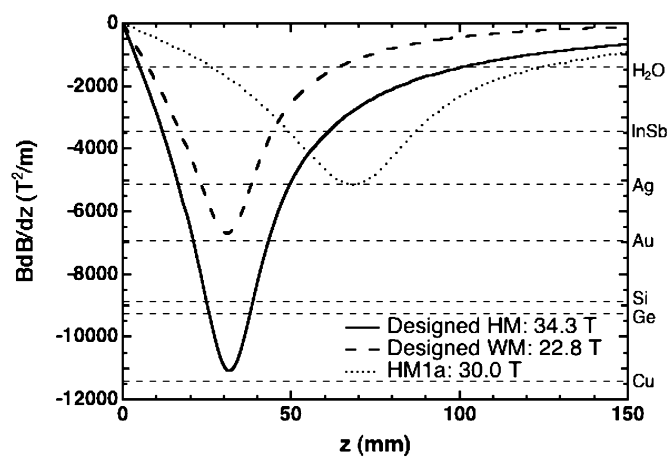

Fig. 4. Calculated magnetic force field distribution of the poly Bitter magnet (broken line) along z-axis, a hybrid mode (solid line) in a backup field of 11.5 T and the existing hybrid magnet HM1a (dotted line). Horizontal broken lines show required value to levitate each material evaluated from the magnetic susceptibility.

where χ_g is the magnetic susceptibility per unit mass of the material, μ_0 is the vacuum permeability, B is a magnetic flux density at distance z from the center of the magnet along the vertical direction. The diamagnetic material has negative susceptibility, and thereby it receives an upward repulsive force if it is placed above the center of the magnet. When the F_{mag} balances with the downward force due to the gravity, the material levitates. The magnetic force field, $B(\partial B/\partial z)$, is an important factor for the magnetic levitation experiment. Fig. 4 shows the position dependence of the magnetic force field of the water-cooled magnet and the hybrid magnet at the central field of 22.8 T and 34.3 T, respectively. The magnetic force field value reaches to about $-11\,100\ \mathrm{T^2/m}$ at $\mathrm{z} = 32\ \mathrm{mm}$ in the hybrid mode. The large value of the magnetic force field is mainly due to a short length of the coils. Even the water-cooled magnet without a backup field can produce $-6,700\ \mathrm{T^2/m}$, and this is larger than that produced by the existing hybrid magnets at the HFLSM. Therefore diamagnetic materials with small $|\chi_g|$, which cannot be levitated now, come to be levitated by using the newly designed water-cooled magnet at the HFLSM. In the case of a 34 T cryogen-free hybrid magnet, the maximum value of the magnetic force field will be $-11\,000\ \mathrm{T^2/m}$ at the central field of 34 T in an 11 T backup field by a wide bore cryogen-free superconducting magnet. The room temperature bore of 16 mm is small to perform a containerless melting experiment but not impossible. A CO_2 laser furnace [12] has been developed in order to perform container-less melting experiments under the magnetic levitation condition so far. An insert of the CO_2 laser furnace is very simple, which mainly consists of a sample cell, a prism and a micro-CCD camera. A levitating sample in the sample cell is irradiated and heated by the CO_2 laser light comes from the outside of the magnet. If the insert is sized down so small as to be set in the bore of 16 mm, the magnetic levitation experiment can be performed sufficiently. The newly designed magnet will play an important role in not only physical property measurements but also materials processing. For a containerless melting experiment under the magnetic levitation condition, a cryogen-free hybrid magnet is more suitable because a cryogen-free hybrid magnet enables to produce a constant high magnetic field for a long term period.

IV. Conclusion

A water-cooled poly Bitter magnet was designed by analytical computations under the condition of an electric power source of 8 MW. The magnet consists of four coaxial Bitter coils. Supposing a backup field is 11.5 T, the designed magnet will produce 34.3 T in a 16 mm room temperature bore. An experimental bore of 8 mm will be available in liquid helium for physical property measurements. An 8 MW and 34 T cryogen-free hybrid magnet will be also realized. The magnetic force field will reach $-11\,100\ \mathrm{T^2/m}$ and is very large enough to levitate diamagnetic materials such as semiconductors.

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