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Water-Cooled Magnet for a 40T Compact Hybrid Magnet*

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A water-cooled poly Bitter magnet for a new compact hybrid magnet was designed under the fully utilization of the electric power source of 8 MW and the cooling systems installed in the High Field Laboratory for Superconducting Materials, Tohoku University. Supposing copper-silver plates with high yield strength are used, a poly Bitter magnet can be designed. 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 tc upper side of coils. The designed poly Bitter magnet will produce 24 T in the room temperature bore of 14 mm and can provide 40 T as a hybrid magnet with backup field of 16 T by the combined superconducting magnet

KEYWORDS: high magnetic field, hybrid magnet, water-cooled magnet, poly Bitter coil.

1. Introduction

Since a hybridmagnet was first built at Francis Bitter National Magnet Laboratory in MIT in 1977[1], the world record of the highest steady field has been renewed one after another. In 1986, the High Field Laboratory for Superconducting Materials at Tohoku University (HFLSM) succeeded to produce 31.1T[2], which was the highest field in the world at that time. Recently a field up to 35.7T was reported as the new record by NRIM[3]. Now the generation of fields over 40 T is considered to be possible and being planned in some facilities in the world[4)-6)]. We also attempt the production of 40 T field at HFLSM.

The progress of the highest field by hybridmagnet is mainly due to the developments of superconducting outer magnet and the employment of a strong electric power for the water-cooled inner magnet. 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 HFLSM, one of the water-cooled magnet produces a field up to 20 T in a space of 32 mm bore at room temperature by 8 MW electric power. If 16 MW power is available, 28 T is possible and 40 T field will be obtained by using 12 T backup field by a superconducting magnet. It seems to be difficult, however, to build a new 16 MW electric power plant at HFLSM due to the budget problem. So we have to consider and design a 40 T magnet with even a small bore by use of existing 8MW power source and cooling system. In our plan, 16 T backup field is to be provided by a newly designed compact superconducting magnet and 24 T field is to be produced by a water-cooled magnet. In this paper we explain the details of design for the water-cooled magnet..

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2. Combined superconducting magnet for backup field

Recently, one of the authors (K. W), developed the new type of $(Nb,Ti)_3Sn$ superconducting wire with Cu-Nb or $Cu\text{-}Al_2O_3$ reinforcing stabilizer[7]. The superconducting wire with Cu-Nb has 0.8 mm outer diameter, 5587 filaments of 3.4 μm diameter and Cu/Cu-Nb/non-Cu ratio of 0.14/0.67/1. While the case of $Cu\text{-}Al_2O_3$ has 1.0 mm outer diameter, 132 filaments of 52 μm diameter and Cu/Cu-Nb/non-Cu ratio of 0.94/0.86/1. The magnetoresistivity of the stabilizer materials were measured in high fields at 4.2 K after the heat treatment, and it was showed that the low magnetoresistivity is 0.15 to 0.17 μΩ-cm at 16 T and 4.2 K, which is merely about two times larger than that of Cu stabilizer.

In general, the critical current density of a superconducting wire is much decreased by the residual strain in the wire. But the newly developed reinforcing $(Nb,Ti)_3Sn$ superconducting wires have the high critical current densities because it is reacted after winding and reduces strain. The experimental critical current densities of the non-Cu parts are 150 A/mm^2 for $Cu\text{-}Nb/(Nb,Ti)_3Sn$ and 300 A/mm^2 for $Cu\text{-}Al_2O_3/(Nb,Ti)_3Sn$ in 14 T at 4.2 K. The 0.2 % proof stresses of the reinforcing materials determined by the measured stress-stain curves were 310 MPa at 4.2 K for $Cu\text{-}Nb/(Nb,Ti)_3Sn$ and 300 MPa at room temperature for $Cu\text{-}Al_2O_3/(Nb,Ti)_3Sn$.

The new multifilamentary superconducting wire enables us to design a very compact superconducting magnet with a large bore and an intense magnetic field because of no housings for external reinforcement and the realization of the large over-all current density. The conceptual superconducting magnet designed for new Tohoku hybrid magnet will generate 16 T at the center of the 360 mm room temperature bore[8].

3. Design of a water-cooled magnet

When a water-cooled magnet is designed to generate a field of 40 T as a hybrid magnet combined with the compact superconducting magnet on the assumption of using the electric power source and cooling systems at HFLSM[9], it is necessary how a magnetic field is generated as high as possible in consideration of the mechanical and thermal limitation of coil materials. Accordingly, the coil shape and the yield strength of the coil materials are very important. Nakagawa[10] made the analytical calculations to obtain the optimum coil shape by treating as the continuous model under the thermal and mechanical limitations. Figure 1 shows the relations between the produced magnetic fields and the dissipated electric power as parameters of inner diameters, d_i, and maximum hoop stress of coils, σ. The field is calculated by the Nakagawa's equation under the back-up field of 16 T. As shown in this figure, it is difficult to produce the field of 40 T in the room temperature bore of 32 mm by 8 MW. Supposing the coil diameter of 20 mm is taken as a necessary room temperature bore of 14 mm for the measurements, the maximum hoop stress of about 500 MPa is required. In the case of an axial water-cooled Bitter coil, the local electromagnetic stress in the disk is enhanced at the part around the cooling hole[11], but it is good enough to take the value of proof stress at a 130 % rate of the maximum hoop stress obtained by the calculation. Therefore, a coil material with the 0.2 % proof stress of 700 MPa is required for safety operation.

In order to make a high-power intense-field 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 in consideration of the electromagnetic stress. However, a making of a polyhelix coil is more difficult than that of a Bitter coil. If the conductor with much higher yield strength than the hoop stress is obtained, it is a good selection that the water-cooled magnet is designed by a Bitter coil. Fortunately, AgCu alloys developed by Sakai et al.[12] have very high yield strength, and so an axial water-cooled poly Bitter coil can be designed. On the design of coils, a copper alloy containing 27 % silver is chosen as the conductor material. The alloy has the electrical resistivity of 85 % IACS and the yield strength more than 900 MPa.

To imitate the coil shape of a Bitter magnet to the optimum coil shape, the poly Bitter magnet was taken. The final designed magnet consists of four Bitter coils. At first the height of each coil is roughly determined and is approached to more and more optimum shape during the computation in consideration of the length of coils, the thickness of conductor disks, the cooling holes distribution and so on. The thickness and the cooling holes distribution of 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 earlier paper[13].

The numerical values and other designed characteristics of the coils are listed in Table 1. Number of the coil is named in order from inner to outer one, e.g. No. 1 coil is the innermost coil. The innermost diameter of the coil is 20 mm and the outermost diameter of the coil is 320 mm. The electric current through the coil is 23 kA and the total across voltage of coils is 347 V. The dissipated electric power is 8.0 MW. When the inlet cooling water temperature is 10 °C and the flow rate of the cooling water is 358 m^3/h, the temperature of the conductor contacting to water is less than 65 °C, and so the maximum temperature

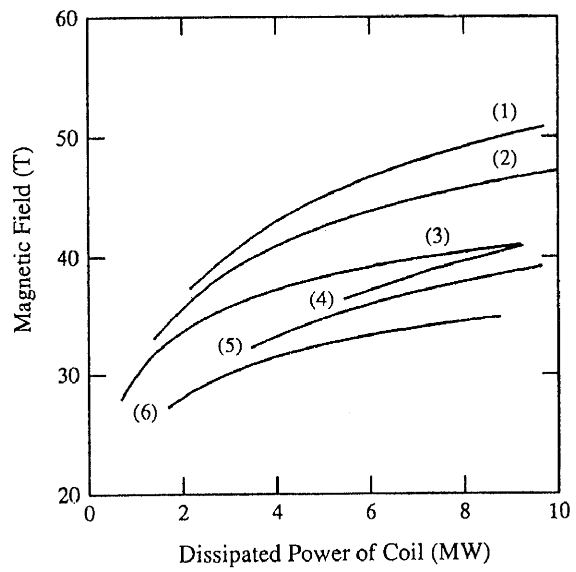

Figure 1. Relation of generated magnetic field versus dissipated electric power of coil for several inner diameter, d_i, and maximum hoop stress, σ. Outer diameter of coil is 320 mm. Packing factor of coil of 0.8 is assumed at any where.

(1) d_i=16mm, σ=700 MPa. (2) d_i=16mm, σ=500 MPa.
(3) d_i=16mm, σ=300 MPa. (4) d_i=40mm, σ=700 MPa.
(5) d_i=40mm, σ=500 MPa. (6) d_i=40mm, σ=300 MPa.

Table 1. The parameter of the designed poly Bitter coil for 40 T hybrid magnet.

	No.1 coil (Innermost)	No.2 coil	No.3 coil	No.4 coil (Outermost)
Inner diameter (mm)	20.0	72.0	142.0	222.0
Outer diameter (mm)	68.0	138.0	218.0	320.0
Coil height (mm)	111.0	148.5	163.4	262.4
Thickness of disk (mm)	2.9	3.2	3.7	4.0
Number of disks	37	45	43	64
Thickness of insulator (mm)	0.1	0.1	0.1	0.1
Number of turns	34	41	39	59
Dissipated power (MW)	0.986	1.614	2.044	3.333
Generated field (T)	8.228	6.605	4.743	4.523
Coil constant (T/kA)	0.658	0.287	0.206	0.197
Resistance of coil (mΩ)	1.86	3.05	3.86	6.30
Hoop stress (MPa)	517.8	511.4	501.4	491.0

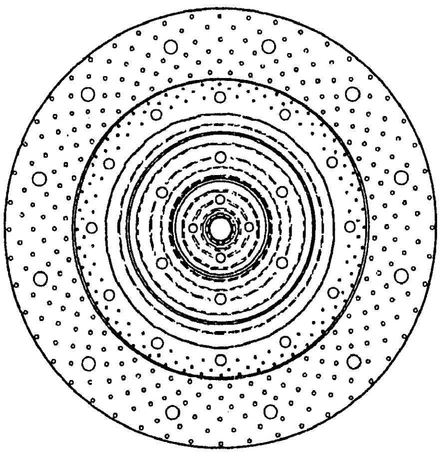

Figure 2. Schematic illustration of the four Bitter disks in a coaxial position. Large holes are bolts holes for stacking the disks.

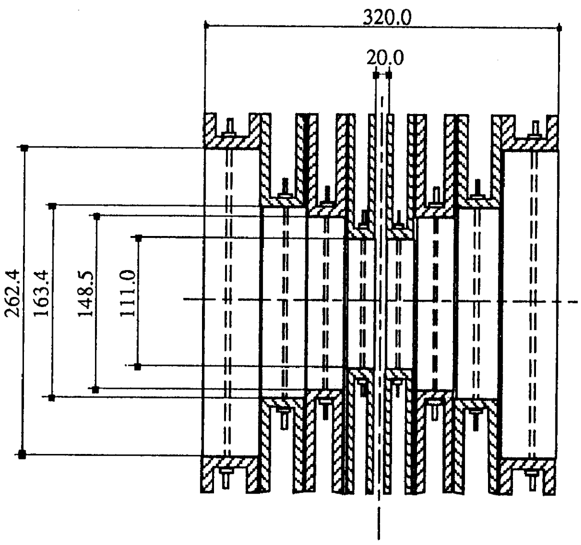

Figure 3. Schematic configuration of the poly Bitter magnet consisting of four Bitter coils. Cooling water flows from the bottom to top in whole coils.

in the conductor is kept below 130 °C. The flow rate of cooling water is 358 m^3/h and is slight larger than the rated flow rate of the cooling system in HFLSM, but it is not so serious problem to cool the coil because the coil disks have enough margin of temperature. The maximum hoop stress is 518 MPa which occurs in the innermost coil. The coil constant is 1.04 T/kA as a whole.

Figure 2 shows the schematic illustration of the four Bitter disks. Slender slots proposed by Weggel[14] 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 relaxation of hoop stress.

Figure 3 illustrates the cross section of the designed poly Bitter coils. The effective coil height and the diameter of the coil are shown. Four coils are electrically connected in series. The cooling water flows from the bottom to the top in whole coils. Hydraulic head loss of the magnet is less than 1.5 MPa in the case of 350 m^3/h flow rate.

4. Conclusion

On the assumption of using CuAg alloy with very high yield strength, a water-cooled poly Bitter magnet was designed under the condition of electric power source of 8 MW. The magnet is constructed by four coaxial Bitter coils. Supposing a backup field is 16 T, the designed magnet will produce 40 T in a 14 mm experimental bore.

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