Construction of a 25-T cryogen-free superconducting magnet

K Watanabe1,*, S Awaji1, H Oguro1, Y Tsuchiya1, S Hanai2, H Miyazaki2, T Tosaka2, M Takahashi2 and S Ioka2

1Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
2Toshiba Corporation, Yokohama 230-0045, Japan

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

Abstract. The construction of a 25-T cryogen-free superconducting magnet (25T-CSM) has started in 2013 at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University. The 25T-CSM consists of a low-\(T_c\) superconducting (LTS) coil and a high-\(T_c\) superconducting (HTS) coil. A high-strength CuNb/Nb\(_3\)Sn Rutherford cable with the reinforcing stabilizer CuNb composite is adopted for the middle LTS section coil. The characteristic feature of the new technology using a CuNb/Nb\(_3\)Sn Rutherford cable is a react-and-wind method for the coil-winding process. The LTS coil of 300-mm winding inner diameter is fabricated, and a central magnetic field of 14 T is generated at an operation current of 851 A. The HTS insert coil wound with GdBa\(_2\)Cu\(_3\)O\(_y\) (Gd123) tape has a 52-mm experimental room temperature bore, and a central magnetic field of 25.5 T will be generated at an operation current of 150 A in a background field of 14 T.

1. Introduction
A cryogen-free superconducting magnet conductively cooled by a tiny GM-cryocooler has been demonstrated in practice in 1992 [1]. At present, cryogen-free high-field superconducting magnets generating 10-15 T are widely used in new research fields such as magneto-science. The distinctive feature of the liquid-helium-free and nitrogen-free operation is the realization of an easy-to-use superconducting magnet. There is no need to supply any liquid helium or nitrogen for the magnet operation.

We have already developed an 18-T cryogen-free superconducting magnet (18T-CSM), which consists of a low-\(T_c\) superconducting (LTS) coil and a high-\(T_c\) superconducting (HTS) Bi\(_2\)Sr\(_2\)Ca\(_2\)Cu\(_3\)O\(_y\) (Bi2223) insert coil. The 18T-CSM generated a magnetic field of 18.1 T in a 52-mm experimental room temperature bore [2]. Recently, the HTS insert coil of 18T-CSM was replaced by employing the high performance Ag/Bi2223 tape, and consequently the magnet was successfully improved to generate 20.1 T [3].

Since a high magnetic field is one of the important physical parameters in condensed matter physics and materials science, the combination of a high field and a cryogen-free superconducting magnet is expected to greatly contribute to the progress of high magnetic field research. In 2013, the construction of the 25-T cryogen-free superconducting magnet (25T-CSM) was funded by the Japanese government at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

*correspondence author

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In this paper, a new technology related to LTS and HTS coils for the 25T-CSM is reported.

2. Design of the magnet system for the 25T-CSM

The magnet system for the 25T-CSM, consisting of an LTS coil and an HTS coil, is shown in figure 1. The parameters of the 25T-CSM superconducting coils are summarized in table 1. Total inductance is 97 H, and stored magnetic energy is 10.7 MJ. The HTS coil, denoted as H1, consists of 68 single-pancake coils. The HTS and LTS coils are individually operated by dual power supplies. The 25T-CSM LTS coil is wound with Rutherford cable conductors. Nb$_3$Sn Rutherford cables are utilized for three coils (L1-L3), and NbTi Rutherford cables are used for two coils (L4-L5). A central magnetic field of 14 T is generated at an operation current of 851 A.

![Figure 1. Schematic view of the 25-T cryogen-free superconducting magnet (25T-CSM).](image)

| Coil ID | H1 | L1 | L2 | L3 | L4a | L4b | L5 |
|---------|----|----|----|----|-----|-----|----|
| Conductor material | Gd123 | Nb,3Sn | Nb,3Sn | Nb,3Sn | Nb,3Ti | Nb,3Ti | Nb,3Ti |
| Operation current | A | 150 | 851 |
| Inner diameter | mm | 102 | 300 | 372 | 458 | 545 | 603 | 628 |
| Outer diameter | mm | 276 | 366 | 452 | 539 | 603 | 622 | 712 |
| Height | mm | 408 | 540 | 628 | 628 | 628 | 628 | 628 |
| Magnetic field contribution | T | 25.7 | 13.7 | 11.3 | 8.37 | 6.83 | 6.22 | 5.84 |
| Width of conductor | mm | 25.7 | 13.7 | 11.3 | 8.37 | 6.83 | 6.22 | 5.84 |
| Thickness of conductor | mm | 5.00 | 6.45 | 6.45 | 6.45 | 6.30 | 5.57 | 5.57 |
| Thickness of layer insulation | mm | 0.13 | 1.83 | 1.83 | 1.83 | 1.80 | 1.61 | 1.61 |
| Space current density | A/mm$^2$ | 125 | 68.9 | 68.9 | 68.9 | 71.6 | 90.0 | 90.0 |
| $T_{cs}$ | K | 5.87 | 7.28 | 8.58 | 5.92 | 6.12 | 6.32 |
| Hoop stress | MPa | 488 | 251 | 243 | 200 | 138 | 112 | 52 |

The current share temperature $T_{cs}$ is 5.87 K for the L1 coil. This results in a temperature margin of over 1.3 K for all coils at an operation temperature of 4.5 K. Concerning the cooling system for the 25T-CSM, the cold mass of the 25T-CSM including the superconducting coils and the structures is 2410 kg. Since the HTS coil with a large temperature margin can be operated at higher temperatures compared to the LTS coil, the cooling structure is separated between the HTS and the LTS coil. To cool the mass, two GM-JT cryocoolers with a cooling power of 4.2 W at 4.3 K are used for the LTS.
coil, and two GM cryocoolers with a cooling power of 1.5 W at 4.2 K are used for the HTS coil. Even if the temperature of the HTS coil rises, the LTS coil temperatures can be kept at a low level owing to the separated cooling structure. The radiation shield is cooled by two single-stage GM cryocoolers with a cooling power of 100 W at 55 K.

The total cooling time from room temperature for the 25T-CSM is approximately 12 d. When the magnet is charged up to 25 T in 60 min, the total heat loads are estimated to be 10.3 W for HTS coils and 4.4 W for LTS coils. Further detailed cooling properties for the 25T-CSM will be reported elsewhere [4]. A large temperature rise due to AC losses limits the magnet sweep rate. We estimated the AC losses for HTS coils on the basis of the Brandt model [5] for a film shape. However, a practical HTS pancake coil will become a bulk shape. Therefore, the designed AC losses for HTS coils are considered to be overestimation, and a ramp-up time will be reduced.

3. React-and-wind method of CuNb/Nb$_3$Sn Rutherford cable superconducting coils

It is worth noting that we developed the high strength Nb$_3$Sn strand with CuNb reinforcing stabilizer (CuNb/Nb$_3$Sn) using the Nb-rod fabrication method [6]. Figure 2 schematically shows the Nb-rod-processed CuNb/Nb$_3$Sn using the drawings of Nb rods embedded into a Cu sheath. CuNb/Nb$_3$Sn compounds were formed by heat treatment at 670 ºC for 96 h, and the characteristics of CuNb/Nb$_3$Sn strands were examined. The CuNb/Nb$_3$Sn strand and Rutherford cable parameters are listed in table 2. As shown in figure 3, the Rutherford flat cable without insulation, composed of 16 strands using a 0.8-mm-diameter CuNb/Nb$_3$Sn strand, is 1.53 mm in width, 6.45 mm in thickness, and 65 mm in twist pitch. A glass epoxy tape is used as an insulating material in 1/4 lap winding. In order to fabricate a coil using a react-and-wind method, the bending treatment for heat-treated Rutherford flat cables was repeated ten times at 0.5% bending strain because we found that the repeated bending treatment significantly enhances the critical current for CuNb/Nb$_3$Sn strands owing to reduction of the residual strain [7].

Figure 2. Fabrication process of Nb-rod-processed CuNb/Nb$_3$Sn strands.

Table 2. Characteristic parameters of (a) the Nb-rod-processed CuNb/Nb$_3$Sn strand and (b) relevant Rutherford cable.

| (a) Strand | (b) Rutherford cable |
|------------|-----------------------|
| Superconductor | Bronze-processed Nb$_3$Sn |
| Reinforcement | Nb-rod-processed Cu-17.4wt%Nb |
| Diameter [mm] | 0.8 |
| Cu/CuNb/non-Cu [%] | 20/35/45 |
| Filament diameter [μm] | 3.3 |
| No. of filaments | 6973 |
| Twist pitch [mm] | 20 |
| No. of strands | 16 |
| Dimensions [mm×mm] | 6.4×1.5 |
| Cabling pitch [mm] | 65 |
| $I_c$ (4.2K, 14.5T) [A] | 1600 < |
The mechanical properties of CuNb/Nb$_3$Sn strands at low temperatures were measured using a tensile stress testing apparatus [8]. The critical currents $I_c$ of CuNb/Nb$_3$Sn strands were determined with an electric field criterion of 1 μV/cm.

The prebending treatment changes the mechanical properties of the CuNb/Nb$_3$Sn strand, suggesting that the mechanical properties are enhanced because of the work hardening of the Cu stabilizer and the CuNb composite by the prebending treatment [9]. The Young’s modulus of the CuNb/Nb$_3$Sn strand changed from 125 GPa for an as-reacted sample to 180 GPa for a prebent sample. Figure 4 shows the stress dependence of $I_c$ for the as-reacted and 0.8% prebent Nb-rod-processed CuNb/Nb$_3$Sn strands. $I_c$ values of the prebent strands under a tensile stress of 230 MPa were higher than those of the as-reacted strands. The peak positions of the $I_c$-stress curves were 210 MPa for the as-reacted strand and 125 MPa for the prebent strand. The hoop stress calculated by Wilson’s model [10] is 251 MPa for the L1 coil. The hoop stress value lies in the mechanical tolerance of the CuNb/Nb$_3$Sn strand. The maximum $I_c$ of 104 A for the as-reacted strand was increased to 112 A by the prebending treatment. These results indicate that the CuNb/Nb$_3$Sn Rutherford cable composed of 16 strands has enough critical current properties over 1600 A in fields up to 14.5 T at 4.2 K [11], because the designed operation current of 851 A for a 25T-CSM LTS coil is approximately half the critical current.

4. GdBa$_2$Cu$_3$O$_y$ (Gd123) superconducting coils with large hoop stress tolerance

As listed in the design parameters of the 25T-CSM HTS coil in table 1, the HTS coil can generate 11.5 T at an operation current of 150 A in a background field of 14 T. In this design, a single bundle
conductor composed of one Gd123 tape is adopted. The maximum radial component $B_r$ of the HTS coil that corresponds to the magnetic field parallel to the c-axis of the Gd123 tape is 4.9 T. Figure 5 shows both field components, the coil-axial field $B_z$ and the coil-radial field $B_r$, in comparison with $I_c$ properties of the Gd123 tape. Considering a Gd123 single bundle conductor, the coil load lines for the operation current of 150 A per one Gd123 tape are compared with the critical current properties. Since the critical currents in fields for $B\perp c$ are very high for the Gd123 tape, the critical currents in fields for $B//c$ limit the coil performance. The hoop stress is estimated to be 488 MPa using Wilson’s model. When the LTS coil happens to quench, a large induced current is added to the operation current for the HTS coil. Since it is very difficult to detect a small voltage due to the hot spot for HTS, we cannot apply the traditional quench protection like a LTS coil system. We found that it is important for an HTS coil design to not have an overcurrent above the critical current. Therefore, the operation current was established below the critical current at 20 K, even in the case of a coil quench for the HTS coil. As a result, the coil performance is limited by the coil radial field $B_r$ for the Gd123 tape.

5. Summary
We are constructing a cryogen-free 25-T superconducting magnet consisting of a low-$T_c$ 14-T superconducting coil and a high-$T_c$ 11-T insert coil. This magnet will generate 25.5 T in a 52-mm room temperature bore, and the magnetic field of 25.5 T would be the highest generated by a practical superconducting magnet to date.

A high-strength CuNb/Nb$_3$Sn Rutherford cable with the reinforcing stabilizer CuNb composite was successfully developed for the middle low-$T_c$ section coil. A new technology of a react-and-wind method using a CuNb/Nb$_3$Sn Rutherford cable is adopted for the coil-winding process. The high-$T_c$ insert coil is fabricated by stacking 68 single-pancake coils using GdBa$_2$Cu$_3$O$_y$ tape.

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