Design of a 30 T Superconducting Magnet using a Coated Conductor Insert

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Design of a 30 T Superconducting Magnet Using a Coated Conductor Insert

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***Abstract*—A program to develop a 30 T superconducting magnet based on novel concepts is now in progress at the High Field Laboratory for Superconducting Materials (HFLSM) at Tohoku University and the Tsukuba Magnet Laboratory (TML) at the National Institute for Materials Science. A 30 T superconducting magnet comprising a high-temperature superconducting (HTS) insert and a low-temperature superconducting (LTS) outsert was conceptually designed. For the high-field HTS insert, a YBCO coated conductor tape was adopted because of its high critical current density in high fields and its high mechanical strength. A relatively high tolerance limit of hoop stress in the insert coil can be assumed in the coil design according to its mechanical properties. The critical current density of the YBCO tape was analytically predicted as a function of temperature and magnetic field. To withstand a large electromagnetic force, the LTS outsert was composed of $\mathrm{CuNb/Nb_3Sn}$ and NbTi coils. The $\mathrm{CuNb/Nb_3Sn}$ coil was designed using high-strength cable consisting of internally reinforced $\mathrm{Nb_3Sn}$ strands with a CuNb reinforcing stabilizer subjected to repeated bending treatment. The results of this design study show the potential for a compact high-field magnet employing an insert coil formed of YBCO coated conductor.**

***Index Terms*—Coated conductor, $\mathrm{CuNb/Nb_3Sn}$, high-field magnet, YBCO.**

I. INTRODUCTION

HIGH-FIELD magnets are now being used in a wide range of research studies. Techniques for generating high field strength have contributed to progress in many areas of research and development. A high-field environment is also important for critical current measurement of superconducting wire samples to improve their characteristics. Such sample materials are often subsequently employed in high-field insert coils. The high-field magnets are typically designed using water-cooled resistive coils, and it consume huge electric power. On the contrary, superconducting magnets consume power only through cooling requirements. As the operating time at user facilities increases, energy-saving and environmental issues must be addressed. To minimize the energy consumption and costs of magnets, a compact design is required by means of increasing the overall current density.

At the High Field Laboratory for Superconducting Materials (HFLSM) at Tohoku University and the Tsukuba Magnet Laboratory (TML) at the National Institute for Materials Science, a program for developing an all-superconducting 30 T magnet based on novel concepts is now in progress [1]. In this work, the conceptual configuration of a superconducting hybrid magnet formed of a high-temperature superconducting (HTS) coil and a low-temperature superconducting (LTS) coil has been preliminarily designed with reference to some representative research studies [2], [3]. A fundamental requirement of high-field magnets is to restrain the large electromagnetic forces sustaining its superconducting property. To attain a high-strength, compact magnet design, a $\mathrm{YBa_2Cu_3O_x}$ superconducting (YBCO) coated conductor was adopted for the HTS insert coil because of its high critical current density (J_c) of more than $1\ \mathrm{MA/cm^2}$ in a magnetic field beyond 25 T [3] and its superior mechanical strength. From a number of progressive studies on YBCO coated conductors, this approach is expected to open the way to a new design concept for high-field magnets. We examined the promise of the high-field YBCO coil design having high overall current density.

II. DESIGN CONCEPT

A. Coated Conductor

1) Current Density: Though various kinds of HTS conductors have been developed, one promising candidate for low-temperature high-field magnets is a rare earth element-based $\mathrm{REBa_2Cu_3O_x}$ superconducting (REBCO) coated conductor. The superconducting characteristics of such coated conductors in magnetic fields beyond 18 T show the potential of practical realization of a 30 T superconducting magnet at liquid helium temperature. As a result of a large number of recent developments, the J_c value of REBCO coated conductors has been significantly improved. For example, a large J_c of $2 \times 10^6\ \mathrm{A/cm^2}$ at 4.2 K and 26 T for the $B//c$-axis has been reported for a YBCO coated conductor fabricated using ion beam assisted deposition (IBAD) and pulsed laser deposition (PLD) [4]. In terms of an engineering product, the current transport characteristic along the longitudinal direction of the tape is also an important aspect. The piece length of a coated conductor fabricated in the recent past is sufficient for the medium-scale magnet in terms of splices in the coils.

On the other hand, the thickness of the superconducting layer included in the coated conductor is two orders of magnitude smaller than that of the metal substrate, so that the engineering current density (J_e) of the coated conductor is significantly reduced. For a compact magnet design, an important issue is the

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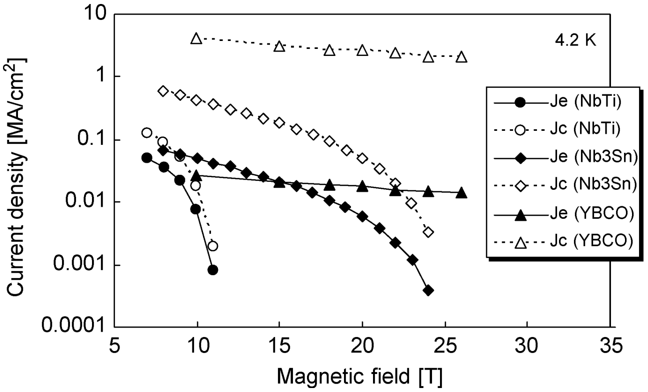

Fig. 1. Engineering current density J_e and core J_c in liquid helium for a NbTi strand, a prebent $\mathrm{CuNb/Nb_3Sn}$ strand, and a YBCO coated conductor.

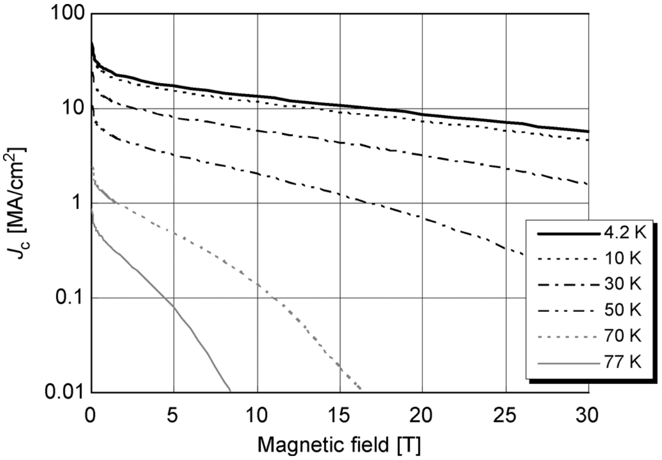

Fig. 2. Calculated critical current density (J_c) of the YBCO coated conductor with artificial pinning centers (APCs) based on a pinning properties analysis as a function of magnetic field perpendicular to the tape.

selected value of J_e. For high-field magnet applications, the J_e value is expected to attain more than $1 \times 10^4\ \mathrm{A/cm^2}$, which is one order of magnitude larger than that of normal copper wiring. Assuming that the multi-layer coated conductor comprises a YBCO layer of 1 $\mu\mathrm{m}$, a metal substrate layer of 100 $\mu\mathrm{m}$, and an additional stabilizing metal layer of about 100 $\mu\mathrm{m}$, J_e of the conductor is reduced to less than 1/200 of J_c.

For this HTS/LTS hybrid magnet design, J_e of the YBCO coated conductor becomes an important parameter in estimating the proper contribution field of the backup LTS coils. The magnetic field contribution of each coil must be determined in terms of increasing J_e of the overall magnet. A comparison of the J_e values of superconductors employed in this design study is shown in Fig. 1 [1]. The J_e of the NbTi strand was estimated using a practical composition that the stabilized copper section is nearly equal to that of the superconducting core. For the $\mathrm{CuNb/Nb_3Sn}$ strands, a J_e value of one-tenth of the J_c value was estimated assuming additional cross sections of bronze, a CuNb reinforcement, and a Cu stabilizer. Comparing the J_e value of $1 \times 10^4\ \mathrm{A/cm^2}$, the field contribution of the NbTi is at most 9 T. For the $\mathrm{Nb3Sn}$, an upper limit of about 18 T is estimated. The J_e of the coated conductor beyond the 14 T crossover point with $\mathrm{Nb3Sn}$ shows the potential of the high field contribution of the HTS part.

In the magnet design, the critical current density of the coated conductor was analytically predicted based on a percolation model and scaling law of the flux pinning properties as a function of temperature and magnetic field [5], [6]. The magnetic field and temperature dependencies of the critical current density of the YBCO tape at the backup-field condition were estimated as shown in Fig. 2. The critical current density of the coated conductor assumed here (thick solid line) is higher than that in Fig. 1 (open triangle), in association with c-axis correlated artificial pinning centers (APCs) [6]. A critical current of 245 A per centimeter of width was assumed for the coated conductor at 77 K, under the self field condition. This corresponds to a critical current of 122.5 A for the 5 mm wide tape assumed here.

2) Mechanical Properties: The high-field insert coil must be designed to fill the requirements for both the critical current in the high magnetic field and the mechanical limits. In concentric long-solenoid coils, the axial electromagnetic force for the insert coil due to the radial component of the magnetic field will not be a serious problem because the magnetic flux in the insert coil is almost aligned with the coil axis. Thus, the problem of stress in the longitudinal direction of the conductor and the radial direction of the solenoid winding must be addressed. The mechanical properties of alloyed metal substrates were measured [7], and the mechanical properties of the coated conductor were confirmed to be dominated by the substrate alone. Regarding the coated conductor itself, excellent stress tolerance of 1000 MPa has been confirmed for a conductor fabricated by an IBAD/MOCVD method with a Hastelloy substrate [8]. In our magnet design, a hoop stress of 420 MPa, calculated from $F = B \times J_e \times r$, where F is the electromagnetic force as the hoop stress, B the magnetic field, and r the coil radius, was set as a maximum tensile stress restriction for the coated conductor in consideration of previously reported results of coil development [9].

B. *Reinforced $\mathit{Nb3Sn}$ Wire*

The LTS outer magnet was composed of $\mathrm{CuNb/Nb_3Sn}$ and NbTi coils. $\mathrm{Nb3Sn}$ conductors are especially sensitive for stress and strain. To withstand a large electromagnetic force, the $\mathrm{CuNb/Nb_3Sn}$ coil was designed using high-strength cable consisting of internally reinforced $\mathrm{Nb3Sn}$ strands with a CuNb reinforcing stabilizer subjected to repeated bending treatment [10]. The prebending process up to 1.0% effectively enhances the critical current of the CuNb reinforced $\mathrm{Nb3Sn}$ conductor. A stranded cable structure consisting of seven round wires was assumed to increase the transport current capacity [11] considering the additional advantage of utilizing the prebending effect. The mechanical strength of the $\mathrm{CuNb/Nb_3Sn}$ stranded cables was governed by the number of stainless steel strands, with a Young's modulus of $E = 200$ GPa. The numbers of constituent stainless steel strands, such as one stainless steel strand (6 + 1) and four stainless steel strands (3 + 4), were designed according to the requirements of both the mechanical and critical current properties. By employing (3 + 4) stranded cables with high strength $\mathrm{CuNb/Nb_3Sn}$ strands, a stress tolerance of over 500 MPa was obtainable at 0.4% strain. The critical current density of the $\mathrm{CuNb/Nb_3Sn}$ wire was estimated using measured data for prebent $\mathrm{CuNb/Nb_3Sn}$ wire

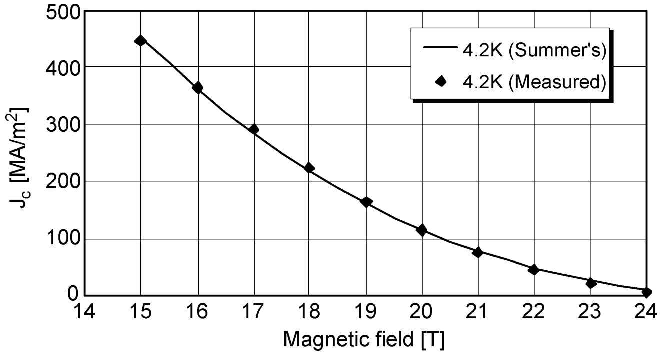

Fig. 3. Critical current density of $CuNb/Nb_3Sn$ wire. Solid line is estimated J_c value from measured data of prebending $CuNb/Nb_3Sn$ wire (closed circle) using by Summer's equation.

samples and Summer's equation [12], as shown in Fig. 3. The filament diameter of the Nb_3Sn sample is 3.5 micron.

III. Design of the Magnet

A. Design Summary

A conceptually designed 30 T superconducting magnet consists of seven sets of concentric coils: three sets of YBCO coils, two sets of $CuNb/Nb_3Sn$ outer coils, and two sets of NbTi outer coils. The coil parameters are listed in Table I. A schematic sectional view of the coils is shown in Fig. 4. An inner winding diameter of 80 mm was set for the innermost coil. The YBCO insert was designed to provide a central field of 16 T, and the outer coils were designed to provide 14 T, for a total of 30 T. First, the magnetic field contribution of the Nb_3Sn outer coils was designed according to the J_e and J_c values shown in Fig. 1, and the design was reviewed to reduce its field contribution in consideration of realistic manufacturing goals of large-diameter Nb_3Sn round wire. In the intended application, the 16 T YBCO insert coil will be wound with IBAD/PLD coated conductor tape of 33 km in length, and the coil weight will be 525 kg. The Nb_3Sn section coils were divided into two grading coils, and 342 MPa hoop stress appeared in the outermost Nb_3Sn layer. The stress is lower enough than the stress tolerance of 500 MPa, which corresponds to 0.4% strain. The critical temperature for the coil, which corresponds to the current sharing temperature, was estimated to be about 7.4–7.5 K for the Nb_3Sn coils and 5.5–6.0 K for the NbTi coils. The magnet was designed to be compact, with a coil inner diameter of 80 mm, a coil outer diameter of 860 mm, and a coil height of 1000 mm, giving a coil inductance of 210 H and a magnetic stored energy of 32 MJ.

B. Superconducting Characteristics of the Coated Conductor

The magnetic field generated by the concentric HTS and LTS coils was calculated for the cross section of the magnet, as shown in Fig. 5. The coated conductor showed unique anisotropic J_c properties with respect to the field angle due to its crystal structure. The J_c values in fields for the $B//$c-axis are usually one order of magnitude smaller than those for the $B//$ab-plane. At any point in the coil cross section, the surface of the coated conductor is parallel to the coil axis, either pancake or layer winding. In the field for the HTS insert, the component perpendicular to the tape surface was relatively small, which is characteristic of a long solenoidal coil. In this design, the field angles between the coil axis and the tape surfaces were distributed almost within a 30 degree range, even at the coil ends. A maximum value of the radial component of the magnetic field, that is, the $B//$c-axis field, of 5.24 T was calculated for the coil C3, which is the outermost coil of the YBCO insert. For simplicity, the absolute value of the magnetic field $|B|$ was used as an assignment operator of J_c ($B//$c-axis) instead of the $B//$c-axis field in this design. The J_c value predicted in this way has an excess margin for the coil current, but this is a safe assumption and is assumed to have no additional adverse effects on the magnet operation.

TABLE I
Design Summary of the 30 T Superconducting Magnet

	Coil 1	Coil 2	Coil 3	Coil 4	Coil 5	Coil 6	Coil 7
Superconductor	**YBCO**	**YBCO**	**YBCO**	**Nb_3Sn**	**Nb_3Sn**	**NbTi**	**NbTi**
Operating current, A	236	236	236	880	880	880	880
Inner diameter, mm	80	150	252	430	541	643	754
Outer diameter, mm	136	238	409	531	632	744	860
Coil height, mm	594	594	840	948	1000	1000	1000
Overall Current density, A/mm^2	112	89.4	81.9	60.4	72.7	59.5	72.8
Field contribution, T	3.89	4.70	7.54	3.41	3.62	3.12	3.73
Maximum field, T	30.03	26.14	21.35	13.64	10.09	7.38	6.07
Conductor shape, mm	5×0.2	5×0.2	5×0.2	Φ1.25	Φ1.13	Φ1.26	Φ1.13
Reinforcement	N/A	0.09	0.13	1/7	1/7	4/7	4/7
Conductor length, km	2.7	6.0	23.9	29.7	21.0	22.4	33.0
Hoop stress, MPa	419	413	399	300	342	200	126

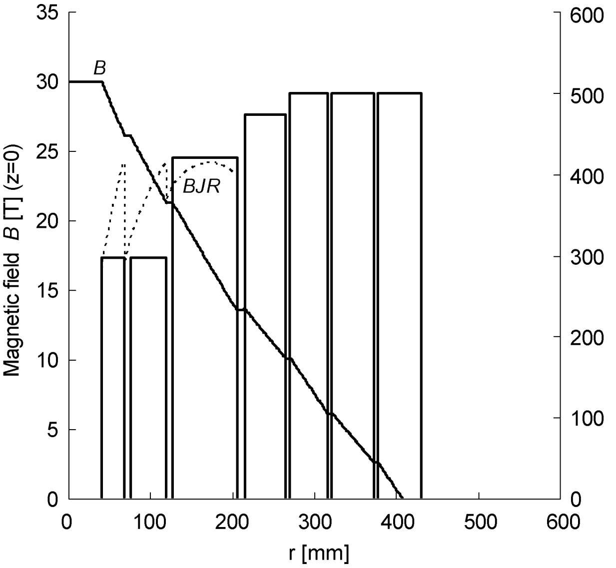

Fig. 4. Calculated magnetic field along the mid-plane of the superconducting magnet. Dotted line shows the hoop stress in the form of $F = B \times J_e \times r$.

C. Mechanical Stress of the Coated Conductor

A relatively high tolerance limit of the hoop stress in the coil winding can be assumed for the high-field insert design based

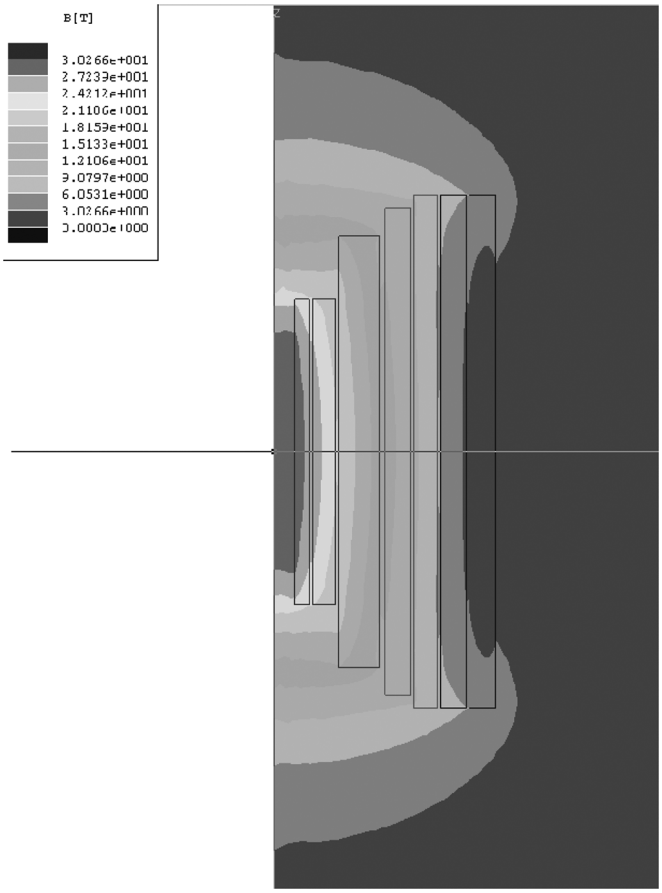

Fig. 5. Calculated results of the magnetic field distribution in the magnet.

on the superior mechanical properties of its alloyed metal substrate. The dimensions and current density of the insert were adjusted so that the tensile stress was less than the maximum value of 420 MPa which is about half the allowed full stress tolerance for the conductor. Although the coated conductor had sufficiently strong mechanical properties, the transport current was restricted by the hoop stress even though the conductor has a larger transport current capacity. To retain the safety stress restriction, a co-winding technique with Hastelloy reinforcement tape was adopted for the YBCO coils C2 and C3 to reduce the apparent J_e of the conductor. For the three winding sections, the conductor cross sectional area of coil C1 was $1.0\ \mathrm{mm}^2$ without reinforcement, which corresponds to a conductor current density (J_con) of $2.4\times10^4\ \mathrm{A/cm}^2$ at 30 T. The cross sectional areas of coils C2 and C3 were $1.45\ \mathrm{mm}^2$ and $1.65\ \mathrm{mm}^2$, respectively, according to the enlarged winding radius. Considering the thickness of the co-wound Hastelloy reinforcement tape, the apparent J_con values of the coils C2 and C3 were $1.6\times10^4\ \mathrm{A/cm}^2$ and $1.4\times10^4\ \mathrm{A/cm}^2$, respectively. In this design, the hoop stress was 419 MPa at most, outside of the innermost coil. As an alternative scheme to adjust J_con, a coil structure composed of winding parts with different tape widths has been suggested to save the trouble of co-winding. Unlike a round wire, a coated conductor with a customized width is relatively easy to fabricate. This winding configuration is one of the features of a coil wound with a coated conductor.

The radial force within the insert coil due to the axial component of the magnetic field increases with increasing winding radius because the relative increment of the radius r is larger than the decrement of the field B. When the winding section is fixed, as in an impregnated coil, the outer turns will pull on the inner turns, further raising the radial stress. Radial tensile stress in the YBCO coil is undesirable because not only does it increase the hoop stress, but it also acts to delaminate the coated conductor [13]. This tensile force is fatally inevitable in an insert coil with a fat shape in a relatively flat backup field. This problem will be considered through adoption of practical design improvements in future.

IV. CONCLUSION

We show a very compact design of a 30 T superconducting magnet comprising a YBCO insert and LTS outer coils. The magnetic field contribution of each coil was determined to increase J_e of the overall magnet. The YBCO insert and the outer LTS parts were designed to provide magnetic fields of 16 T and 14 T, respectively, in terms of a suitable magnetic field region for J_e. Though there remain some unresolved issues to attain a practical magnet design, the coated conductor is considered to be a promising solution compared with Bi-based superconductors for low-temperature, high-field applications.

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