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20 T Compact Superconducting Outsert Employing Y123 Coated Conductors for a 45 T Hybrid Magnet

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***Abstract*—We have been developing high-strength Nb_3Sn strand cables to construct a high-field superconducting outsert for a 45 T hybrid magnet with a 25 T water-cooled resistive magnet. Evidence for cold work strengthening of repeated bending treatment (prebending effect) on Nb_3Sn strands internally reinforced with CuNb stabilizer, which exhibits significant enhancement of the critical current density, has been found in the superconducting magnet fabrication process using a react-and-wind method. The strand cables were designed by controlling the constituent number of $CuNb/Nb_3Sn$ strands with the prebending effect and stainless steel strands, which are expected to have a stress limit 580 MPa at 0.4% strain. In order to design a compact superconducting outsert, high-strength strand cables are adopted in a magnetic field region below 14 T to maintain relatively large engineering current densities (J_e). In a higher-field region above 14 T, $YBa_2Cu_3O_7$ (Y123) coated conductors are employed for an insert coil. Using combination of Y123, Nb_3Sn and NbTi superconductors, a 20 T superconducting outsert with a room temperature bore of 400 mm consisting of three layers made of Y123, two layers of $CuNb/Nb_3Sn$ and two layers of NbTi was designed. The coil parameters are 440 mm inner diameter, 1080 mm outer diameter and 1138 mm coil height. A very compact 20 T superconducting outsert with a stored magnetic energy 72 MJ at an operation current 903 A can be developed for a 45 T hybrid magnet.**

***Index Terms*—High magnetic field, hybrid magnet, Nb_3Sn, react-and-wind process, YBCO coated conductor.**

I. INTRODUCTION

HIGH MAGNETIC fields are highly expected as one of the fundamental extreme environments for research of materials science and engineering. The research using static high fields up to 30 T has presented many important achievements in frontiers such as high-T_c superconductors, heavy electron system, low-dimensional semiconductors, and organic conductors. In the future, high-field science will require further strong fields up to 40–50 T in the world [1]. A problem encountered is how such a magnet producing 50 T should be made and how a magnet technology realizing it should be developed.

For high-field facilities constructed in the world, a tremendous electric power from 20 to 30 MW is required to use a water-cooled resistive magnet [2]. It is difficult to build huge research laboratories and maintain enormous electrical charges in the universities. From the consideration of energy-saving and environment issues, a superconducting technology leading to the smallest electric power consumption should be attempted to develop a static high field magnet. On this basis, we propose a compact design of a 20 T superconducting outsert employing $YBa_2Cu_3O_7$ (Y123) coated conductors and high-strength Nb_3Sn strand cables for a 45 T hybrid magnet, which will be combined with 25 T-15 MW water-cooled resistive magnet.

In this paper, a high-T_c superconducting outsert consisting of a low-T_c background coil is compared with a traditionally designed all low-T_c superconducting outsert wound with Nb_3Sn and NbTi superconductors. A magnet size and a stored magnetic energy are demonstrated to extremely reduce by approximately 50%, employing Y123 coated conductors with the large engineering current density J_e in fields above 14 T.

II. CONDUCTOR DESIGN

A. LTS Conductors for a Background Coil

We have been developing a new Nb_3Sn cabling process adopting a react-and-wind method as shown in Fig. 1 [3]. In this process, the J_c enhancement effect due to the prebending treatment was clearly found for high-strength Nb_3Sn strands reinforced with CuNb composites $(CuNb/Nb_3Sn)$ [4]. The neutron diffraction experiment denoted that such a prebending treatment extremely reduces residual strain in radial and lateral directions for $CuNb/Nb_3Sn$ strands [5]. Since the stress level required for the 20 T superconducting outsert with a 400 mm room temperature bore is over 500 MPa, the large I_c degradation will occur even in a high-strength $CuNb/Nb_3Sn$ strand. In order to withstand the huge electromagnetic stress, a stainless steel strand with Young's modulus $E = 200$ GPa was additionally used for reinforcement of strand cable conductors. We designed that the stainless steel strands mainly support the external stress of 580 MPa and $CuNb/Nb_3Sn$ strands experience the maximum strain 0.4%. According to the requirements of both mechanical and critical current properties, the constituent number of the stainless steel strand and the $CuNb/Nb_3Sn$ strand was determined. In this magnet design, the 4+5 strand cable conductor consisting of four $CuNb/Nb_3Sn$ strands and

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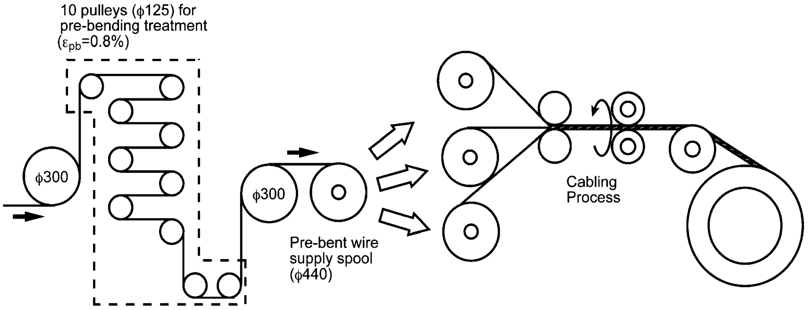

Fig. 1. High-strength $\mathrm{CuNb/Nb_3Sn}$ cabling process using a react-and-wind method.

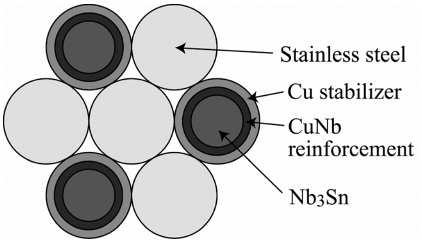

Fig. 2. Cross sectional view of a 3 + 4 high-strength $\mathrm{CuNb/Nb_3Sn}$ strand cable conductor composed of four stainless steel strands.

five stainless steel strands was supposed to have the current capacity of 1000 A at each contributed field and at 2.2 K under the stress tolerance 580 MPa at the strain limit 0.4%. Recently, we successfully demonstrated the react-and-wind cabling process of 100 m long 3 + 4 strand cable conductors, as the practical application of the prebending strain effect. Fig. 2 shows the cross sectional view of fabricated 4 + 5 strand cable conductors. After the cabling process, we confirmed that there is no $\mathrm{I_c}$ degradation of $\mathrm{CuNb/Nb_3Sn}$ strands [6]. Concerning the compressive stress, we are now planning to develop Cu-sheathed 3 + 4 strand cable conductors with solder impregnation.

B. HTS Conductors for a High Field Insert Coil

Since the excellent performance of the critical current density $\mathrm{J_c}$ in fields up to 27 T at 77.3 K for CVD-processed Y123 films was demonstrated for the first time in 1989 [7], the development of practical long-length Y123 coated conductors has been actively carried out by both CVD-IBAD and PLD-IBAD method. The $\mathrm{J_c}$-vs-B properties at 4.2 K for the CVD-IBAD Y123 coated conductor fabricated by Chubu Electric Power Company were estimated by a flux pinning scaling law. The Y123 superconductor has the anisotropy of the superconducting properties due to the 2-dimensional crystal structure. Usually, the $\mathrm{J_c}$ values in fields parallel to the c-axis (B//c) for Y123 coated conductors are one order of magnitude smaller than those perpendicular to the c-axis $(\mathrm{B} \perp \mathrm{c})$. $\mathrm{J_c}$ values estimated at 30 T and 4.2 K for the CVD-IBAD Y123 coated conductor are $2 \times 10^6\ \mathrm{A/cm^2}$ for $\mathrm{B} \perp \mathrm{c}$ and $2 \times 10^5\ \mathrm{A/cm^2}$ for B//C. When the CVD-IBAD Y123 coated conductor will contribute to an insert coil, it may be possible to design such a coil using the $\mathrm{J_c}$ properties in fields for $\mathrm{B} \perp \mathrm{c}$, because the B//c component in the insert coil is estimated to be less than about 5 T from a point of the coil assemble configuration. This means that we can use $\mathrm{J_c} = 2 \times 10^6\ \mathrm{A/cm^2}$ at 30 T and 4.2 K for magnet design. In addition, recent great progress on the $\mathrm{J_c}$ improvement for the PLD-IBAD Y123 coated conductor enables us to obtain the further high $\mathrm{J_c}$ value of $2 \times 10^6\ \mathrm{A/cm^2}$ at 4.2 K at 30 T even for B//c [8], and in particular the outstanding high $\mathrm{J_c}$ value of $6 \times 10^6\ \mathrm{A/cm^2}$ at 4.2 K at 30 T for B//c [9] may be obtainable, introducing artificial pinning centers (APC) such as $\mathrm{BaZrO_3}$ and $\mathrm{BaSnO_3}$ [10]. Therefore, it is expected that such artificial pinning centers can also enhance the $\mathrm{J_c}$ values in CVD-IBAD Y123 coated conductors. Fig. 3 shows the comparison of $\mathrm{J_c}$ among CVD-IBAD processed, PLD-IBAD processed and PLD-IBAD with APC (PLD-IBAD/APC) processed Y123 coated conductors. It was found that core-$\mathrm{J_c}$ characteristics in fields up to 30 T for a PLD-IBAD Y123 coated conductor present the average and standard performance between CVD-IBAD processed and PLD-IBAD/APC processed Y123 coated conductors.

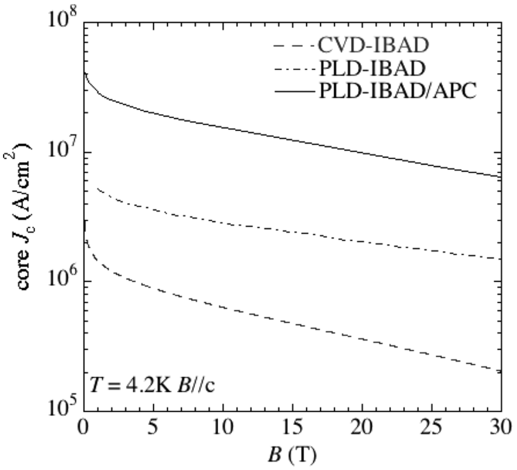

Fig. 3. Comparison of core-$\mathrm{J_c}$ among the CVD-IBAD processed, the PLD-IBAD processed, and the PLD-IBAD with artificial pinning centers (PLD-IBAD/APC) processed Y123 coated conductors.

Furthermore, for concerning the mechanical properties of Y123 coated conductors, we have verified the sufficient ability in the hoop stress experiment using a 250 mm bore Y123 coated conductor test coil at 11 T and 4.2 K. It was found that the Y123 coated conductor can withstand the hoop stress over 770 MPa even in the Hastelloy outer coil configuration. We expect that the Y123 double pancake winding method can also withstand the large compressive stress using a reinforcing insulation plate between double pancakes.

TABLE I
COIL PARAMETERS OF THE ϕ400–20 T SUPERCONDUCTING OUTSERT FOR A 45 T HYBRID MAGNET

Coil ID		L1	L2	L3	L4	L5	L6	L7
superconductor		Y123			CuNb/Nb_3Sn		NbTi	
superconductor size	mm	0.2×7.3	0.2×7.3	0.2×7.3	ϕ1.07	ϕ0.91	ϕ1.26	ϕ0.96
reinforcement	–	1+6(Hx)	1+6(Hx)	1+6(Hx)	4+5(SUS)	4+5(SUS)	3+4(SUS)	3+4(SUS)
conductor length	km	2.0	2.9	3.8	7.9	13.3	9.8	18.6
inner diameter	mm	440	516	591	667	780	892	989
outer diameter	mm	506	581	657	770	882	979	1080
coil height	mm	623	764	896	1042	1141	1138	1138
operation current	A	903	903	903	903	903	903	903
overall current density	A/mm^2	88.4	88.4	88.4	94.7	131	104	178
field contribution	T	1.96	2.00	2.02	3.14	4.09	2.58	4.23
central field	T	20.0	18.1	16.1	14.0	10.9	6.81	4.23
hoop stress	MPa	402	420	424	442	541	272	251

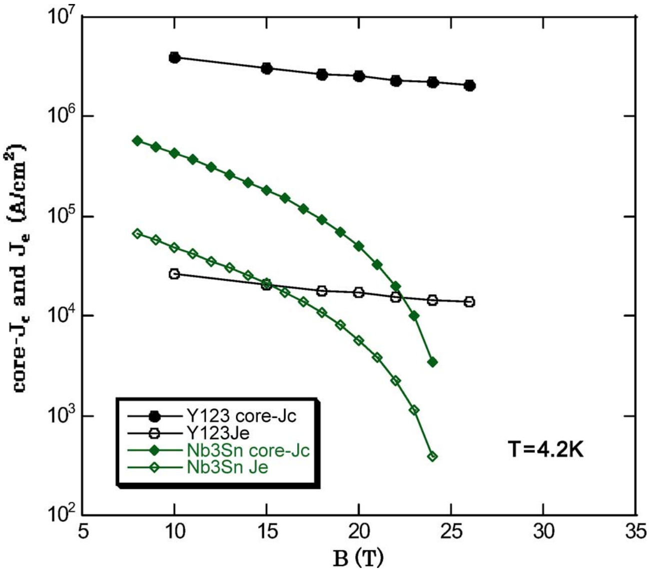

Fig. 4. Core-J_c and J_e for the $CuNb/Nb_3Sn$ strand and the PLD-IBAD Y123 coated conductor.

C. Comparison of Core-J_c, J_e, and Overall-J_c

One should note that J_c is defined as the superconducting core J_c (core-J_c), in order to clarify various current densities i.e. the superconducting core J_c, conductor overall J_c, and coil average J_c for magnet design. The magnet design is actually influenced by not a superconducting core J_c (core-J_c) but an overall J_c (overall-J_c) of the average conductor critical current density. However, overall-J_c largely depends on a reinforcement method, such as a stainless steel strand for Nb_3Sn cables and a Hastelloy co-winding tape for Y123 coated conductors. Moreover, we focused on the superconductor critical current density through the whole superconductor cross section called as the engineering current density (J_e).

Fig. 4 shows the comparison of core-J_c and J_e for the $CuNb/Nb_3Sn$ strand and the Y123 coated conductor. The bronze route Nb_3Sn strand internally reinforced with CuNb composite has 10 times larger non-superconducting cross section than Nb_3Sn superconducting cores. As a result, the $CuNb/Nb_3Sn$ strand with prebending treatment exhibits $J_e \approx 1/10 \times \text{core-}J_c$. On the other hand, the architecture of PLD-IBAD and CVD-IBAD Y123 coated conductors is specialized by a very thin 1–2 μm Y123 core, a 10 μm thick Hastelloy substrate, and a $(20+80)$ μm thick (silver + copper) stabilizer [11]. In the case of Y123 coated conductors, therefore, J_e is two orders of magnitude smaller than core-J_c. When the $J_e = 1 \times 10^4$ A/cm^2 criterion for making a practical superconducting magnet is utilized, we can understand the limit of an 18 T generation employing Nb_3Sn superconductors under the condition of 4.2 K. In order to make a 20 T superconducting outsert compactly, we should adopt the adequate superconductors with the larger J_e values more than 2×10^4 A/cm^2. That is, the larger J_e is obtained in low fields below 14 T for $CuNb/Nb_3Sn$ strands. Principally, the conductor overall current density (overall-J) including the reinforcing materials at the operation current is utilized for magnet design. Especially, a high-field superconducting magnet with a wide bore requires a large amount of reinforcement for superconductors employed in a high-field region. This means that the average current density for the Y123 coated conductors will be extremely reduced as the overall-J, because of very thick reinforcing Hastelloy tape. To keep an overall-J as largely as possible, we have to desire the further improvement of core-J_c for PLD-IBAD Y123 coated conductors introducing strong c-axis correlated artificial pinning centers (APC), for instance.

III. MAGNET DESIGN

The coil parameters designed for a 20 T superconducting outsert are listed in Table I. On the basis of the larger J_e, the 20 T superconducting outsert is composed of a 14 T $CuNb/Nb_3Sn$ and NbTi background coil and a 6 T Y123 insert coil. The Y123 insert coil is divided into three layered coils, and six 200 μm thick Hastelloy tapes (1.2 mm thick) are co-wound for reinforcement. This means that the core-J_c value of 1×10^7 A/cm^2 at 20 T and 2.2 K for Y123 coated conductors is reduced to $J_e \approx 5 \times 10^4$ A/cm^2. However, one notices that the conductor current density including the additional reinforcement of Y123 coated conductors is as small as overall-J $\approx 8.8 \times 10^3$ A/cm^2 (88 A/mm^2) at the operation current 903 A.

The designed 20 T superconducting outsert with a room temperature bore of 400 mm has the coil parameters of 440 mm inner diameter, 1080 mm outer diameter, and 1138 mm coil height. The very compact 20 T superconducting outsert with a stored magnetic energy 72 MJ at an operation current 903 A, which is reduced to be as small as 50% in comparison with the

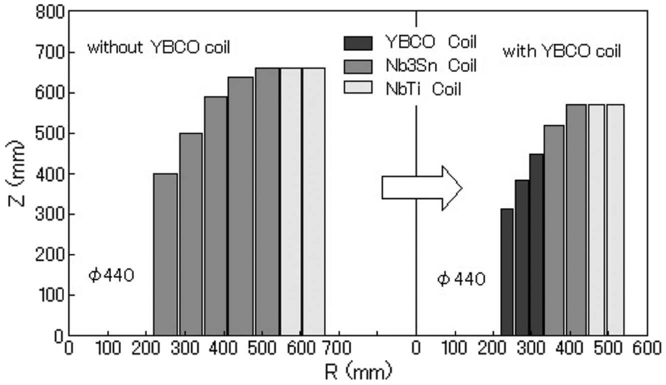

Fig. 5. Comparison of the 20 T superconducting outsert size with and without the Y123(YBCO) coated conductor insert.

all low-$\mathrm{T_c}$ superconducting outsert reported so far, can be developed for a 45 T hybrid magnet.

As can be seen in Fig. 5, we understand how compactly the 20 T superconducting outsert will be realized. When the 20 T superconducting outsert will be fabricated by employing only low-$\mathrm{T_c}$ superconductors, the coil size is 1332 mm outer diameter and 1321 mm coil height. As a result, thestored magnetic energy was estimated to be 144 MJ. It was found that the designed values for the low-$\mathrm{T_c}$ 20 T superconducting outsert are limited by the core-$\mathrm{J_c}$ values of $\mathrm{CuNb/Nb_3Sn}$ strands in high fields. On the contrary, it is emphasized that the design limitation of the high-$\mathrm{T_c}$ superconducting outsert changes from the small critical current density value to the large mechanical stress value in high fields.

IV. CONCLUSION

In order to construct a compact and laboratory-easy- operation 45 T hybrid magnet, a 20 T–ϕ400 mm room temperature bore superconducting outsert was designed employing high strength $\mathrm{Nb_3Sn}$ strand cables and Y123 coated conductors. $\mathrm{Nb_3Sn}$ strand cable coils were adopted in low fields below 14 T to keep relatively large $\mathrm{J_e}$ values. The coil parameters are ϕ440 mm inner diameter, ϕ1080 mm outer diameter, and 72 MJ stored magnetic energy at 903 A operation current in a superfluid helium bath at 2.2 K.

It was found that the coil size and the stored magnetic energy of the designed outsert with Y123 coated conductors is reduced to be as small as 50% in comparison with the previously reported outsert employing all low-$\mathrm{T_c}$ superconductors.

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