DESIGN OF THE TF COIL FOR A TOKAMAK FUSION POWER REACTOR WITH YBCO TAPE SUPERCONDUCTORS

T. Ando[a] and S. Nishio[b]
[a]Nippon Advanced Technology Corporation, 801 Mukaiyama, Naka-shi, Ibaraki, 311-0102 Japan
[b]Japan Atomic Energy Research Institute, 801-1, Mukaiyama, Naka-shi, Ibaraki,311-0193 Japan

***Abstract*— A low aspect ratio tokamak, VECTOR was designed by Japan Atomic Energy Research Institute (JAERI) to provide the high cost performance necessary for a commercial power reactor. The maximum magnetic field within the winding of the toroidal field (TF) coil is about 20 T. The applicability of high temperature superconductor YBCO tape to the TF coil conductor is considered. YBCO tape is well known to have higher critical current density. However, YBCO tape has magnetic instability due to flux jumps. The magnetic field at which the first flux jump occurs is estimated to be 6.8 T at 33 K. Therefore, to prevent flux jumps, the winding is divided into three (higher, middle and lower field) winding packs and the maximum self magnetic field produced by each winding pack is less than 6.8 T. The low field winding pack is cooled first down to 33 K and operated up to its nominal current. In this case, the middle and higher field winding packs are maintained above 90 K. Next, in similar process the middle pack is operated. Finally, the higher pack is operated, and 20 T is generated without flux jump. The nominal current for every winding pack is 40 kA. Thus it is possible to apply YBCO tape to the TF coil and YBCO tape will be expected to play an important role in the realization of tokomak fusion power reactors with low construction and operation costs, and high performance plasma.**

Keywords-fusion reactor; VECTOR; YBCO; flux jump; 20 T coil

I. INTRODUCTION

For the development of tokomak fusion power reactors following ITER, VECTOR, which is designed with low aspect ratio to realize high normalized beta, is considered at JAERI [1]. The maximum field within the TF coil winding is designed to be about 20 T. The TF coil was initially designed using Bi2212 wire with an operation temperature of 20 K [2]. However, the development of YBCO wires having higher critical current density is rapidly progressing. A YBCO tape with over 250 m length was fabricated; using this tape a small coil was wound, which achieved 0.72 T at 66 K [3]. YBCO tape with a current density of more than 12000 A/mm^2 at 20 T and 30 K has been developed [4]. The combination of coil operation at high temperature and a simple coil configuration with high stiffness structure due to indirect cooling system is expected to provide lower operating costs. On the other hand, the large size of the YBCO conductor may produce magnetic instability due to flux jumps and high hysteresis loss. The applicability of YBCO tapes to the TF coil of a tokamak fusion reactor is considered in this paper.

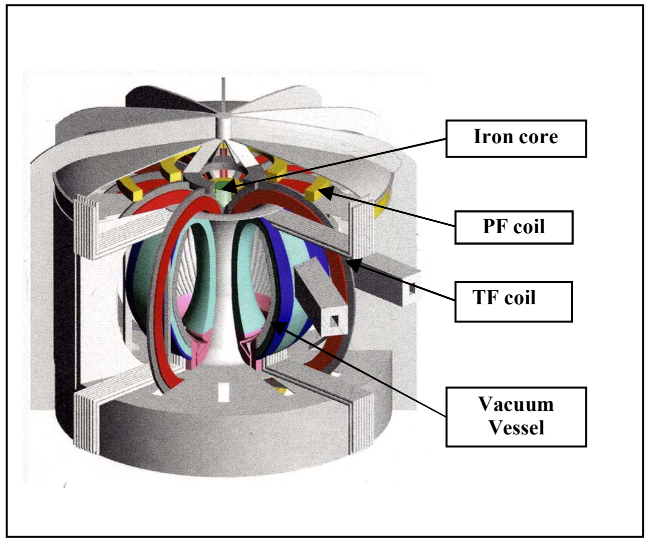

Figure 1. Concept of VECTOR－MOD

Solutions are proposed for the most important issues on the application of the YBCO tape to the TF coils. A concrete design is presented for the conductors and TF coil structure for VECTOR-MOD which is modification of VECTOR with an iron core provided in the center of the TF coil system.

II. APPLICABILITY OF YBCO TAPE TO LARGE CURRENT CAPACITY CONDUCTORS FOR FUSION

A. Jc of YBCO Tape

At present YBCO tape has the highest critical current density among superconducting wires. Fig. 3 shows its Jc performance compared with that for the Nb_3Sn conductor applied to the ITER coils. The Jc for YBCO is more than 12000 A/mm^2 at 20 T and 30 K [4]. The Jc of Nb_3Sn wire is denoted by non-copper area. However, YBCO wire is fabricated by physical or chemical processes which are different from the metallurgical process used for the fabrication of Nb_3Sn and BSSCO wires. Therefore, YBCO wire is fabricated with tape shape. At present the production rate for YBCO tape is very slow. Recently, the development of YBCO tape production using the TFA-MOD process has progressed, and commercial YBCO tapes with high production rate and low cost are expected soon [5].

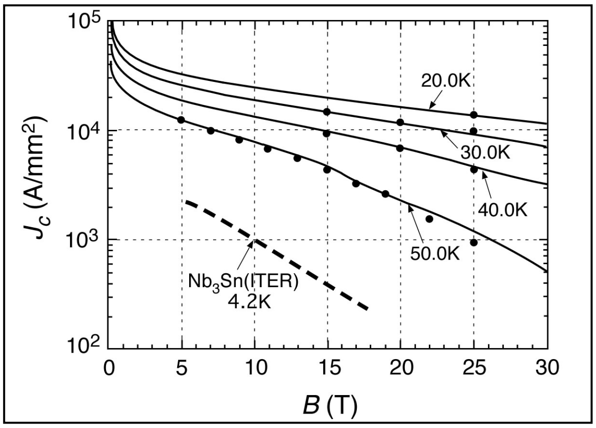

Figure 2. Jc vs. B performance for YBCO tape compared to the Nb_3Sn strand applied to ITER.

B. *Flux Jump of YBCO Type*

As the external magnet field on a bulk superconductor increases from zero, flux jumps are typically observed at a certain value. Flux jumping was a major factor for the quench of early superconducting coils. To prevent the occurrence of flux jumps, commercial superconducting wires such as Nb_3Sn and BSSCO are composed using a number of fine superconducting filaments whose diameters are less than about 50 µm. It is very difficult to construct YBCO tapes using fine superconducting filaments. The magnetic field (B_{fj}) where flux jump occurs for YBCO is calculated by (1) [6].

$$B_{fj} = (3\,\mu_o\,\rho\,C\,(T_c - T_o))^{1/2} \qquad (1)$$

where μ_o is the permeability, ρ is the density, C is the specific heat, T_c is the critical temperature, and T_o is the operating temperature, respectively. Fig. 3 shows the relationship between B_{fj} and temperature when the size of the superconductor is infinite. B_{fj} increases with increasing temperature below about 60 K. B_{fj} is 6.8 T at 33 K. These values are much higher than B_{fj} (below 1 T) for Nb_3Sn. Therefore, when YBCO tape is used for the TF coils, the design should account for the much higher B_{fj} for YBCO.

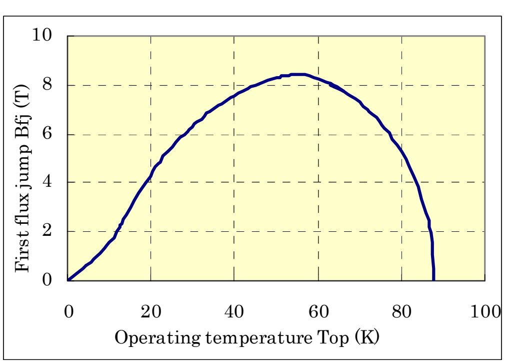

Figure 3. B_{fj} as a function of the operating temperature (T_o) in YBCO tape.

C. *AC Loss of YBCO Type*

Generally, as the size of the superconductor material within a conductor increases, the hysteresis loss per cycle also increases. However, when the size of superconductor material is sufficiently large, its hysteresis loss again decreases. The calculation of hysterics loss in YBCO tape as a function of the tape width is shown in Fig. 4, for various varying fields perpendicular to tape and with Jc = 10000 A/mm^2. Hysteresis loss increases with size for narrow tapes, but decreases with size when the tape size is more than 0.1 mm. The hysteresis loss in 50 – 100 mm wide tape is smaller than that in 1 mm wide tape.

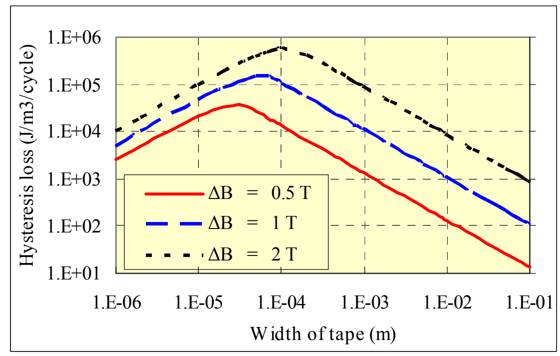

Figure 4. Hysteresis loss as a function of tape width for various magnetic fields in YBCO tape.

III. DESIGN OF YBCO CONDUCTOR

The stabilization of the YBCO conductor against the disturbances such as movement etc. is designed to be done with the enthalpy of the YBCO material itself, rather than by cooling with supercritical helium. Figure 5 shows specific heat for YBCO as a function of temperature. The specific heat at 33 K is 220 mJ/cm^3/K. For the temperature range between 33 and 35 K, the conductor has a heat capacity of 500 mJ/cm^3. This value is considered to be sufficient to stabilize the conductor against likely disturbances.

The TF coil is designed with an operating current of 40 kA, a maximum field of 20 T at the winding and an operating temperature of 33 K. Three kinds of YBCO conductors, 20 T, 13.4 T and 6.7 T-conductors are provided for the TF coil. The structure of the 20 T-conductor is composed of four identical YBCO tapes as shown in Fig. 6.

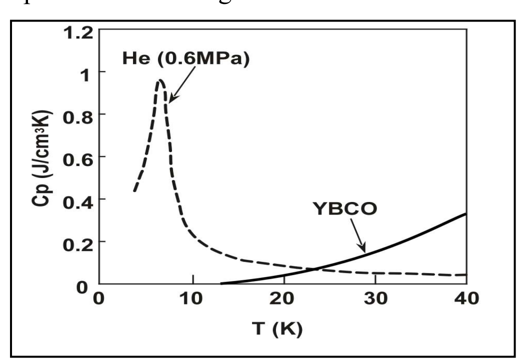

Figure 5. Specific heat as a function of temperature in YBCO material in comparison of supercritcal helium.

TABLE I. PARAMETERS OF THE CONDUCTORS

	20 T conductor	13.4 T conductor	6.7 T conductor
Size including insulation (mm^2)	101x 6	81 x 6	51 x 8.4
Maximum magnetic field (T)	20	13.4	6.7
Nominal operating current (kA)	40	40	40
Operating temperature (K)	33	33	33
Width of Tape (mm)	101	81	51
Thickness of YBCO (mm)	0.04	0.04	0.04
Thickness of copper sheet (mm)	4	4	6.4
Critical current dennsity (A/mm^2)	11,000 at 20 T	14,000 at 13.4 T	22,000 at 6.7 T

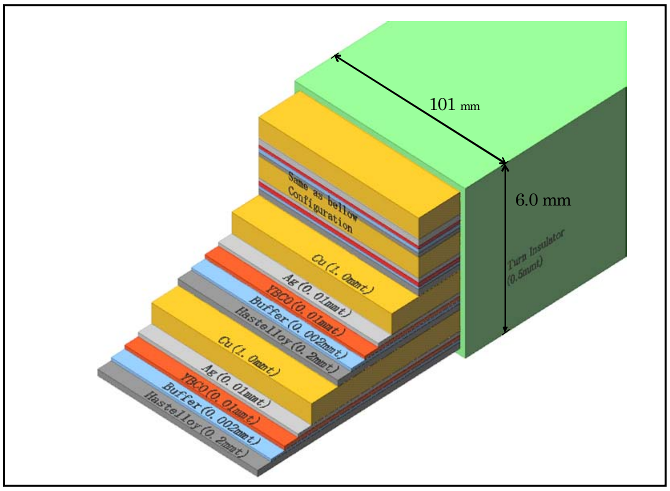

Figure 6. A 20 T 40 kA 33 K YBCO conductor

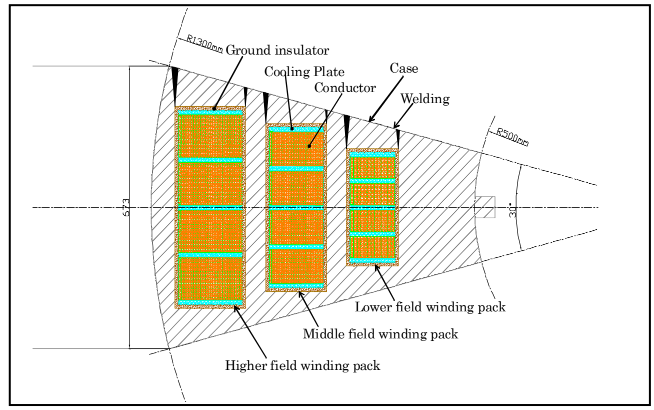

Figure 7. Cross-section of the winding at the mid-plane in the inner leg.

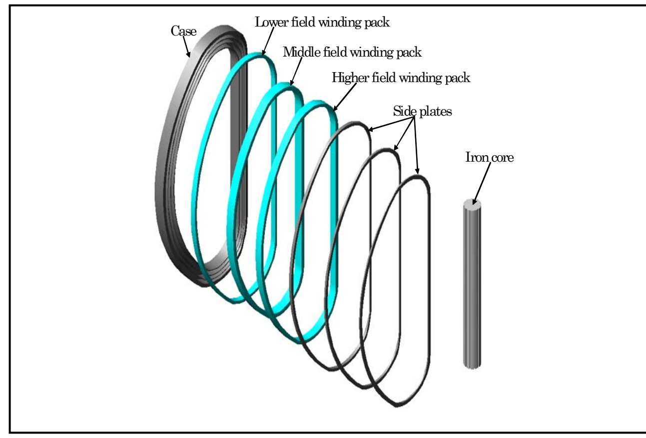

Figure 8. Expanded view of a TF coil

The tape the YBCO material in the tape is coated on top of a buffer material on a hastelloy substrate and a copper sheet is soldered through a silver film on the YBCO layer, as protection against quenching. The thickness of copper sheet is decided as 2 mm based on a temperature rise limitation of 200 K under the condition of a quench detection time of 2 s and a dump time constant of 10 s. The width of tape is 100 mm and the thickness of each YBCO layer is 10 µm. The designed Jc is selected to be 11,000 A/mm^2 at 20 T and 33 K from Fig 4. The YBCO conductor is wrapped with an insulator of 0.5 mm thickness. The total size of 20 T-conductor has a width of 101 mm and a thickness of 6 mm. The applied strain on YBCO layer is estimated to be 0.18 % as the bending strain during winding and 0.09 % as the operation strain during coil operation for the limitation strain of 0.3 % [7]. The other conductors are designed with a configuration similar to that for the 20 T conductor.

IV. COIL STRUCTURE

The TF coil consists of 12 coils; each coil has a height of 12 m and a width of 7 m for the inner bore. Each coil has three (higher, middle and lower field) winding packs installed into the coil case. To reduce stress (or strain) on the winding, three slots are machined into the coil case in which each winding pack is installed. Each winding pack is fabricated as a pancake winding using a react-and-wind process. Cooling plates, which are made of Cu and CuNi, are provided between the pancakes and at both sides of every winding pack. After the winding pack is wrapped with a fiber-reinforced material and kapton for ground insulation, it is installed into one of the slots in the case. The slot is then closed by welding on a case cover. The cross-section of winding at the mid-plane in the inner leg is shown in Fig. 7. An expanded view of the coil is shown in Fig. 8. The parameters of the TF coil for VECTOR-MOD designed are listed in Table II along with those for the TF coil of ITER. VECTOR-MOD is designed more compactly than ITER.

There are two kinds of joints (pancake-to-pancake joint and double pancake-to-double pancake joint) in the TF coil. The most important issue for joints between conductors which are composed of four tapes is the generation of coupling currents induced between the tapes due to varying magnetic fields. The coupling currents produce heat generation at the joints and can lead to a transition to the normal state due to over current excitation in the tapes. To reduce the tendency towards coupling current generation, each of the four YBCO tapes in the conductor at the pancake-to-pancake joint is connected alternately with each of the four YBCO tapes of the other conductor as shown in Fig 9 (a) [8]. At the double pancakes-to-double pancake joint, the both conductors are connected normally as shown in Fig. 9 (b).

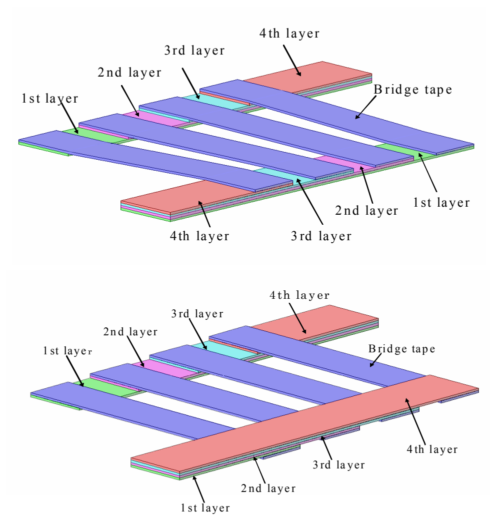

Figure 9. Joint configuration. (a) : pancake-to-pancake joint (upper) and (b) :idouble pancake-to-double pancake joint (lower).

TABLE II. PARAMETERS OF THE TF COILS FOR VECTOR-MOD AND ITER

	VECTOR-MOD	ITER
Size (m x m)	7 x 12.6	7 x 12
Number of coils	12	18
Maximum field within winding (T)	20 T	12.8 T
Superconducting wire	YBCO tape	Nb_3Sn strand
Nominal current (kA)	40	68
Operating temperature (K)	33	4.6
Number of turns/coil	244	134
Amper-turn (MA)	117.12	164
Magnetic stored energy (GJ)	32	41
Current density in coil (A/mm^2)	25.9	6.4
Terminal voltage (kV)	12	15
Time constant during dump (s)	10	11
Cooling method	Conduction	Forced cooling

V. OPERATION PROCESS

The TF coil is operated using three power suppliers for the higher, middle and lower field winding packs. The same kind of winding packs for every coil is connected in series. The series of lower field winding packs only is cooled first down to 33 K and operated up to 40 kA corresponding to the maximum field of 6.7 T, while the other winding packs are kept above 90 K. For the next step, the series of middle field winding packs is cooled down to 33 K and operated up to 40 kA under the background field of 6.7 T. Finally, the series of higher field winding packs is operated up to 40 kA at 33 K under the background field of 13.4 T and the maximum field of 20 T is achieved without the occurrence of flux jumps.

VI. CONCLUSION

The applicability of YBCO tape to the TF coil of a fusion power reactor has been considered within the existing conductor database.

1. By increasing the cool operating temperature because YBCO tape has high critical current density at higher temperature, the magnetic field where the first flux jumping occurs can be increased and the enthalpy margin of YBCO conductor can be increased. Furthermore, the construction and operation costs of cooling system are decreased. The consumption of energy to cool the coil at 33 K is reduced by about 15 % compared to that for cooling at 4.5 K.

2. The fabrication of 20 T TF coils with YBCO tapes is possible due sub-division into three winding packs that can be independently temperature-controlled. The maximum self field for each winding pack is limited to below 6.8 T to avoid the occurrence of flux jumps in the YBCO tapes.

3. Hysteresis loss in YBCO tapes subjected to time-varying fields from the PF coils is reduced because the width of the tape is much larger than 1 µm..

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