Research of HTS Application on Tokamak Magnets

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***Abstract*—in this paper, the application feasibility of HTS tapes on tokamak magnets is discussed and the existing four kinds of HTS high current conductors are summarized. Furthermore, an YBCO conductor structure suitable for a 10 GJ tokamak TF magnet is designed and the current carrying capacity is evaluated. The simulation result shows that the critical current of the YBCO conductor is about 75 kA @ 10 T, 30 K.**

Keywords-HTS Application; Tokamak Magnets; YBCO conductor

I. INTRODUCTION

It is essential to use superconducting coils for future fusion power generation devices to decrease the electric energy consumption and thus ensure the magnet systems operating safely and stably. From the mid-seventies to the late eighties, the applications of superconductivity on tokamak entered a golden age, with plenty of large devices and prototype coils being developed in Russia, US, Japan and Europe. The increase of dimensions and stored energy drove an interesting variety of conductor and coil design. So far, these superconducting coils are all made of low temperature superconducting cable-in-conduit conductor (LTS CICC), such as NbTi, NbZr and Nb3Sn. Because of the transverse load degradation and self-field induced quench, it is difficult for LTS CICC to be larger dimensions. Therefore, it is urgent to design next generation tokamak conductors.

With the development of HTS materials, it is possible for HTS conductors to be applied in tokamak magnets. Compared to LTS magnets, HTS magnets can greatly save cooling cost and have better thermal stability. In ITER, first generation (1G) HTS conductors have been used for some components such as current leads and bus bars. Moreover, Bi-2212 wires have been previously bundled into Rutherford cables for magnet applications. But, as some relevant problems, such as high current conductor and coil development, and high-cost obstacle to the use of HTS materials, have not yet been resolved, HTS conductors have not been introduced into tokamak magnets on a large scale. At present, YBCO commercial products have been available. The mechanical properties are better than that of BSCCO [1]. In the near future, if single YBCO tape can be made long enough to meet the requirements for winding tokamak coils and the cost fall down greatly, YBCO tapes will go into practical application on tokamak magnets.

In this paper, the application feasibility of HTS tapes on tokamak magnets is discussed and the existing four kinds of HTS high current conductors are introduced. Furthermore, an YBCO high current conductor structure suitable for tokamak magnets is designed and the critical current is calculated.

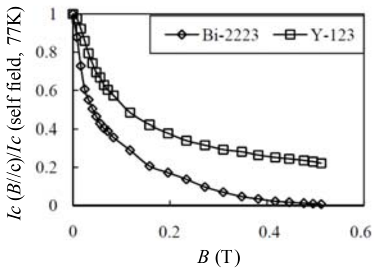
II. HTS MATERIALS MAY BE APPLIED IN TOKAMAK MAGNETS

There are two possible options for HTS materials used in tokamak magnets: 1G BSCCO and 2G YBCO conductors. Bi-2212 is the only HTS conductor which can be produced as a round multi-filamentary wire. Therefore, it is isotropic and conventional winding methods could be used. But it is brittle and strain sensitive. The Bi-2223 multi-filamentary tape has a strong anisotropy. The engineering critical current densities of Bi-type conductors are in the range of 70-125 A/mm2 (77 K, self-field). The minimum bending radius is 25 mm. A typical maximum axial tensile stress value is in the range of 200-250 MPa (77 K). The critical currents of Bi2223 decrease rapidly with the increasing of the magnetic field at temperatures above 50 K. In order to obtain higher critical current densities and lower field sensitivity, all present application of BSCCO have operating temperatures lower than 30 K [2]. At 77 K, the perpendicular magnetic field that Bi2223 can withstand is below 1T [3].

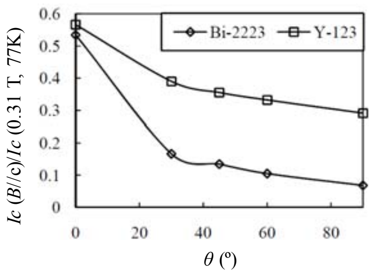
The engineering critical current densities of YBCO coated conductors (CCs) are in the range of 200-400 A/mm2 (77 K, self-field). The tensile stress of up to 700 MPa can be tolerated with no irreversible degradation of critical currents (about 0.6% strain). The minimum bending radius is about 10 mm. Compared to Bi-type conductors, the in-field performance and mechanical properties have been improved greatly. Even at fields well above 10 T, the operation temperatures are high enough to make a profit. They have high critical currents at relatively high temperature (less than 50 K) and that makes it feasible to be cooled by cryocoolers instead of by liquid helium. YBCO had already been proposed to be applied in tokamak magnets in 2004 [4].

Figure 1 shows the electromagnetic characteristics of Bi2223 (made by Innost, China) and YBCO (made by SuperPower, USA) obtained by experiments. The tests have been finished in liquid nitrogen. When a HTS conductor is applied in magnetic field perpendicular to the tape surface, the critical current of Bi2223 falls faster than that of YBCO does. When the magnetic field angle θ (the angle of the tape surface and the magnetic field) changes, it has a less effect on the critical current of YBCO than it does on that of Bi2223.

Briefly, YBCO CCs have more potential to be used for tokamak magnets because of its impressive performance.



(a) Normalized current dependent on external field



(b) Normalized current dependent on angle θ

FIGURE I. ELECTROMAGNETIC CHARACTERISTICS OF BI2223 AND YBCO.

III. DEMONSTRATED CONDUCTOR DESIGN

A. Concept Demonstration of High Current Conductors

There are four kinds of high current HTS conductors that have been proposed. They are the rectangular conductor type, Rutherford cable type [5], helical winding cable type [6] and helical twisted stacking-tape cable type [7].

In 2001, a Bi2212 conductor was designed for the TF coil of A-SSTR2. It is composed of a rectangular HTS cable and a rectangular copper cable (see Figure 2). The conductor is cooled by a rectangular cooling channel which contacted its one side surface. The operating temperature is 20 K. The critical current density is 1000 A/mm2 at 20 K and 23T.

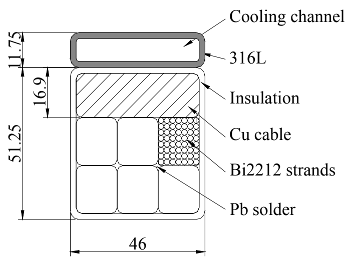


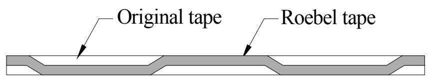
FIGURE II. STRUCTURE OF RECTANGULAR CONDUCTOR TYPE.

In 2005, Roebel technique was applied for YBCO CCs to achieve high current carrying capabilities for low ac-loss application. In 2011, S. I. Schlachter, et al, developed Roebel cables consisting of up to 50 tapes with current carrying capabilities up to 2.6 kA (77 K, self-field) and presented a concept for CC Rutherford cable using Roebel subcable as strands. Figure 3 shows the structure.

Another approach is a REBCO CC helically winding cable which is constructed by spiral-winding tapes around an insulated round copper cable former (see Figure 4). Each superconducting layer is wound in the direction opposite to the winding direction of its neighboring layer. The cable consists of 24 tapes in 8 layers (3 tapes per layer). The individual CC has Ic of about 125 A at 76 K. The critical current of the cable is 2.8 kA at 76 K, self field.

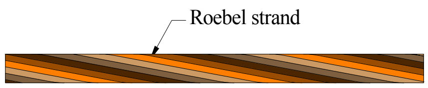
The forth approach is to twist stacked-tape cable in a shaped former. Figure 5 shows three-helical-groove CICC of 32-YBCO- tapes in each groove. A stacked and twisted conductor of 96 YBCO tapes (Ic = 90 A) in three grooves may carry approximately up to 1.53 kA current at 77 K, self field.

The four demonstrated designs indicate that HTS materials, especially YBCO could be made into high current conductors for large coils, such as tokamak magnets. The first design is similar to LTS CICC conductor. It is a good choice only for Bi2212 round conductor. The other three designs can be applied to 2G HTS tapes. The Rutherford cable type needs to cut out a part of the conductors so as to strand them into a rectangular cable. Hence, the cost is relatively expensive. The third approach is not adequate for much higher current cables because there is much difference between the tape lengths of each layer. For the fourth approach, it may be not easy for the cable to be cooled by cryogenic liquid because of lack of cryogenic liquid channels in the cable interior.



(a) CC tape cut to Roebel tape

(b) Roebel strand



(c) Rutherford cable

FIGURE III. STRUCTURE OF RUTHERFORD CABLE TYPE.

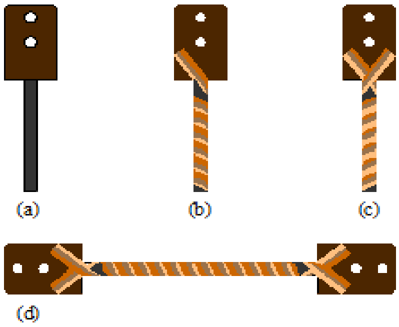
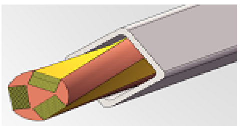


FIGURE IV. STRUCTURE OF HELICALLY WINDING CABLE TYPE.

(a) A stacked-tape cable twisted with a twist pitch

(b) Three helical grooves in a rod



(c) Three-helical-channel CICC cable

FIGURE V. STRUCTURE OF TWISTED STACKING-TAPE CABLE.

B. *Design Requirements*

High current conductors are usually made by conductor strands in parallel. In order to minimize nonuniform current distribution at different location, the strands have to transpose each other along the length of the conductors. The thin and flat shape is a barrier for HTS tapes to be twisted repeatedly.

In general, HTS conductors for tokamak should meet these conditions: they should have high-current and high in-field engineering current density windings; be flexible and mechanically robust; and have low conductor anisotropy, low magnetization losses. In addition, it is necessary to keep a certain ratio of copper to superconductor for stabilizing conductor and quench protection although the ratio could be reduced greatly considering that YBCO conductors usually conclude copper stability layers. Above all things, the conductor design must consider the operating condition of the HTS coils.

In the design of HTS coils, the operating temperature of the coil is a key issue. When operating temperature is 30 K instead of 4.5 K, the capacity of cryogenic system is expected to be reduced by about 40% [8]. Furthermore, the mechanical performance of structural materials are decreased if YBCO tapes operating at more than 30 K. Therefore, 30 K is chosen as the operating temperature. In this paper, a high current conductor is designed for a future tokamak TF coil with 50 kA nominal current and 10 T maximal magnetic field. Considering the design margin, the critical current of the HTS conductor will be designed as 75 kA @10 T, 30 K. The temperature rise of the conductor due to Joule heat generation during quench is less than 200 K. The terminal voltage of the TF coil is limited to 20 kV. What follows is a design of an YBCO high current conductor. The main parameter requirements are listed in Table 1.

TABLE I. PARAMETERS OF THE HIGH CURRENT CONDUCTOR.

Critical current (10 T, 30 K)	75 kA
Maximum field	10 T
Operating temperature	30 K
Ratio of copper to superconductor	>1: 4
Jc in YBCO at 30 K and 10 T	>100 A/mm^2
YBCO: Cu: Ag of a CC tape	1: 40: 2
Copper cross section	300 mm^2

IV. PHOTOGRAPHS AND FIGURES

A. *Conductor Configuration*

According to the above principles and parameter requirements, an YBCO conductor design is given in Figure 6. YBCO tapes from SuperPower Inc. are used. The width and thickness of a single tape are 4 mm (some of them are 2 mm) and 0.095 mm, respectively. The corresponding critical currents are 120 A for 4 mm width tape and 60 A for 2 mm width tape.

The conductor is mainly composed of three parts: a former, YBCO tape stack groups and a stainless tube. The former, which is made of a copper rod of 30 mm diameter, has four helical grooves which are orthogonal.

In each groove, there are 5 twisted rectangular YBCO stacks. They constitute nearly 1/4 of the cross section. In order to fix the YBCO tapes, they are sandwiched with two 0.1 mm copper strips at the bottom and top of each stack. The stacks are twisted with a twist pitch of 180 mm. Four stack groups and the former form a 30-mm-diameter circle and are embedded in a tube of 32 mm outer diameter. The center hole and the gap outside the circle can serve as cooling channels. The detailed parameters are shown in Figure 7.

(a) A twisted stacked-tape conductor with a twist pitch of 180 mm.

(b) The former with 4 helical grooves

(c) The four-helical-channel CICC conductor

FIGURE VI. THE STRUCTURE OF THE CICC CONDUCTOR.

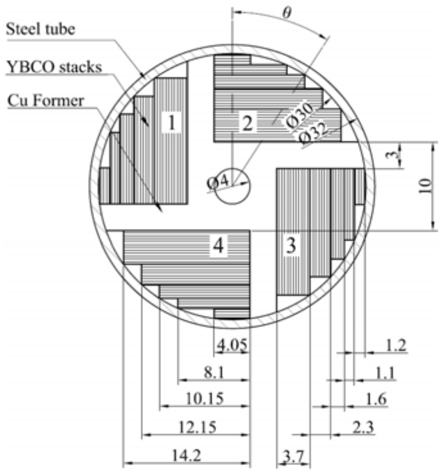


FIGURE VII. THE CROSS SECTION OF THE CONDUCTOR.

B. Conductor Configuration

The in-field critical current of a HTS tape should be determined by the crossing point of the load line and the critical current characteristic curve of the YBCO tape. When the critical current of a single tape in self-field is determined, the critical current of the CICC conductor could be calculated. Therefore, in the critical current calculation, we must measure current density dependence on magnetic field characteristic curve (*Ic*-*B* curve) and find out the load line of the HTS tape. Figure 8 is the experimentally obtained *Ic*-*B* curve of SCS 4050 YBCO tape at different magnetic field angles. The normalized current is shown in Figure 9.

From Figure 9, it can be seen that the critical current degradation is greater in the normal magnetic field, especially in the perpendicular field, than in the parallel one. Furthermore, the current degradation becomes more severe with the increase of the magnetic field *B*. When *B* is 0.05 T, the critical current in perpendicular field ($Ic_{\perp B}$) is 70.5% of that in parallel field, 77 K, self field ($Ic_{//B,\ 77\ K,\ self\ field}$). When *B* is 0.55 T, $Ic_{\perp B}$ drops down to 22% of $Ic_{//B,\ 77\ K,\ self\ field}$.

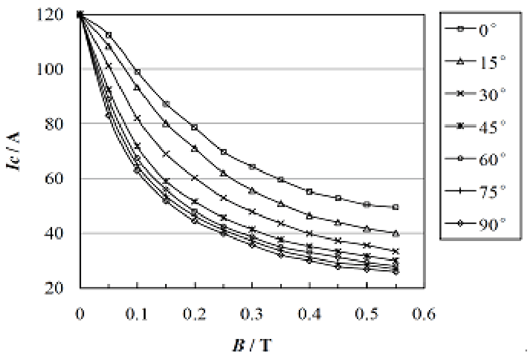


FIGURE VIII. CRITICAL CURRENT OF YBCO TAPE, 77 K.

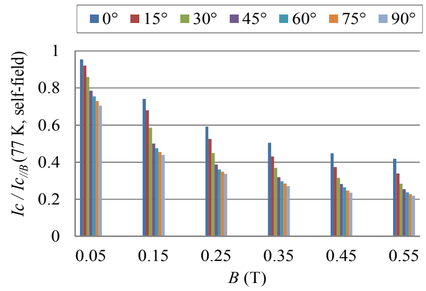


FIGURE IX. NORMALIZED CURRENT OF THE YBCO TAPE, 77 K.

C. Conductor Configuration

For the CICC conductor, when the magnetic field is perpendicular to the surfaces of YBCO stacks 2 and 4 (θ = 90°), it is parallel to those of stacks 1 and 3 (θ = 0°). Thus, current redistribution occurs, and YBCO stacks 1 and 3 will share more current than stacks 2 and 4. Therefore, compared to the case of magnetic field perpendicular to all 4 tape surfaces, the whole current carrying capacity has a promotion. Figure 10 shows the normalized current of the YBCO CICC conductor at different field angles (θ =0°/ 90°, 15°/75°, 30°/60° and 45°/45°), which is the mean value at two different magnetic field angles.

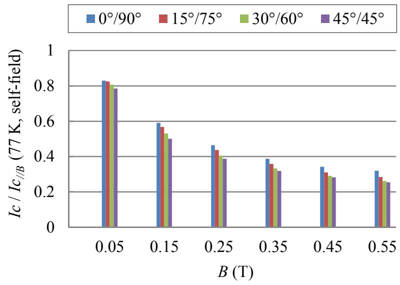


FIGURE X. MEAN NORMALIZED CURRENT OF THE YBCO CICC CONDUCTOR, 77 K.

When *B* is 0.05 T, the mean critical current in 45º field ($Ic_{\angle 45^{\circ}B}$) is the least among those in the normal magnetic field, which is 78.5% of $Ic_{//B,\ 77\ K,\ self\ field}$, and $Ic_{\angle 0^{\circ}B}$ is about 83% of $Ic_{//B,\ 77\ K,\ self\ field}$. When *B* is 0.55 T, $Ic_{\angle 45^{\circ}B}$ is 32% of $Ic_{//B,\ 77\ K,\ self\ field}$ and $Ic_{\angle 0^{\circ}B}$ is 25.5% of $Ic_{//B,\ 77\ K,\ self\ field}$. Compared Figure 10 with Figure 9, it can be seen that anisotropy of the YBCO CICC conductor becomes weaker than that of the single YBCO tape.

D. Conductor Configuration

To get the load characteristic, we assume that each tape of the conductor is fed with 120 A for a 4 mm width tape or 60 A for a 2 mm width tape. Then, the magnetic field distribution of the conductor could be found by simulation. As the critical current of the tape in perpendicular magnetic field is the lowest, the perpendicular magnetic field components applied on the tapes in two quarters of CICC conductor and then parallel magnetic field components in the other two are calculated as shown in Figure 11 (a). Furthermore, for the CICC conductor, as the critical current at 45º field is the lowest, Figure 11 (b) shows 45º magnetic field distribution of the tapes in two quarters of CICC conductor.

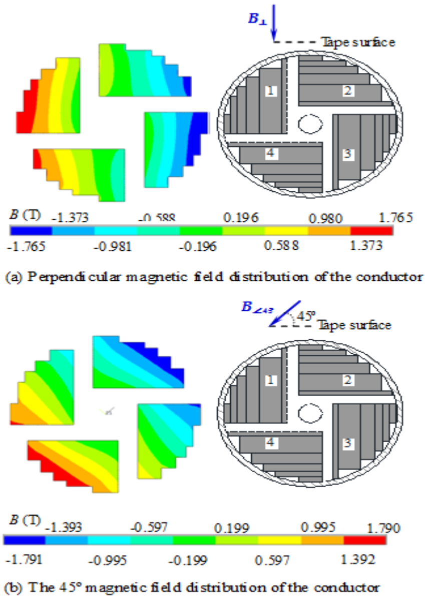


FIGURE XI. MAGNETIC FIELD DISTRIBUTION OF THE CONDUCTOR AT 77 K, SELF FIELD.

From Figure 11, it can be seen that the maximum vertical and 45 º magnetic fields are 1.765 T and 1.791 T, respectively. The intersecting points of the magnetic field characteristic and the corresponding load characteristic curves are the critical operating points. The lower of two values is the critical current of single tape in the CICC conductor at 77 K, self-field. Figure 12 shows the critical current of the CICC conductor at 77 K. For convenience, the current values are all expressed as that of a single tape in the CICC conductor.

Because the amount of the tapes is certain, the critical current of the CICC conductor can be calculated if the critical operating point of a single YBCO tape is found out. The critical current of the CICC conductor is the sum of the critical current of each single YBCO tape at magnetic field.

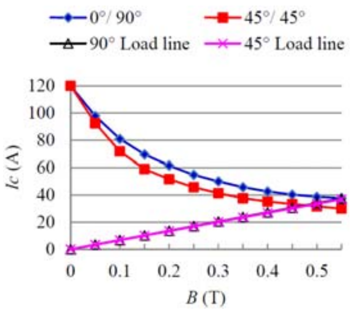


FIGURE XII. MAGNETIC FIELD AND LOAD CHARACTERISTIC AT 77 K.

From Figure 12, it can be seen that: When θ is 0º or 90º, the critical current of a single 4 mm width tape is 37.59 A at 0.55 T, 77 K, and it is the maximal value. When θ is 45º, the critical current is minimal, which is 32.16 A at 0.48 T, 77 K. The CICC conductor consists of 940 YBCO tapes of 4 mm width and 208 YBCO tapes of 2 mm width. Hence, the critical current of the YBCO CICC conductor is conservatively estimated at 33.5 kA at 0.48 T, 77 K.

E. Conductor Configuration

Similarly, we can obtain the critical current of CICC conductor at 30 K. Assuming each tape of the conductor is fed with 120 A for a 4 mm width tape or 60 A for a 2 mm width tape, the corresponding magnetic field components applied on the tapes are simulated as shown in Figure 13.

The maximum vertical and 45º magnetic fields are 10.696 T and 10.854 T, respectively. Then, the load lines and magnetic field characteristic curves of a single YBCO tape in the CICC conductor dependent on perpendicular and 45º magnetic field can be depicted in Figure 14. The current values are expressed by the lift factor [Ic (30 K)/ Ic (self field, 77 K)] from SuperPower Inc.

As shown in Figure 14, when θ is 0º or 90º, the lift factor of a single 4 mm width tape is 3.34 at 6 T, 30 K. When θ is 45º, the lift factor is 2.78 at 5 T, 30 K. When the conductor is applied in 10 T, 30 K, the lift factor is 2.24. Considering the sum of YBCO tapes and Ic (self field, 77 K), the critical current of the YBCO CICC conductor is about 75 kA @ 10 T, 30 K.

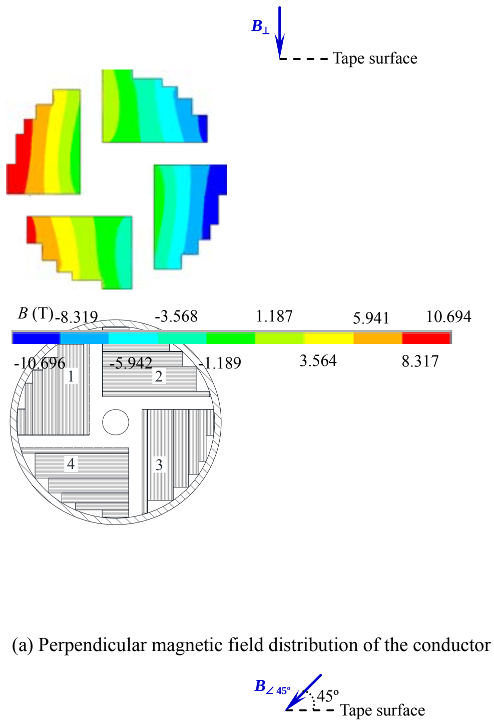


FIGURE XIII. THE MAGNETIC FIELD DISTRIBUTION OF THE CONDUCTOR AT 30 K.

V. Conclusion

Compared to 1G HTS conductors, 2G HTS tapes show higher in-field critical current and better mechanical properties. The four demonstrated designs indicate that HTS materials, especially YBCO materials could be used for high operation current tokamak magnets.

An YBCO CICC conductor for a 10 GJ tokamak concept magnet is designed. It includes a copper former with 4 helical grooves, a stainless tube and 4 YBCO tape stack groups which consist of 940 YBCO tapes of 4 mm width and 208 YBCO tapes of 2 mm width. It is easy to be cooled by cryogenic liquid or gas. The calculation shows that the critical current values can get to 33.5 kA @ 0.48 T, 77 K and 75 kA @ 10 T, 30 K.

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