Test of 10 kA-Class HTS WISE Conductor in High Magnetic Field Facility*)

Yoshiro NARUSHIMA[1,2], Yoshiro TERAZAKI[1], Yuta ONODERA[1], Nagato YANAGI[1,2], Naoki HIRANO[1], Shinji HAMAGUCHI[1], Hirotaka CHIKARAISHI[1], Tomosumi BABA[1] and Junichi MIYAZAWA[1,2]

[1]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan*
[2]*The Graduate University for Advanced Studies, SOKENDAI, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan*

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High-temperature superconducting (HTS) conductor is a feasible candidate to make magnets for the next generation fusion devices because of its higher temperature margins and higher critical current in a high magnetic field in comparison to low-temperature superconducting (LTS) conductors. The recently proposed concept of the HTS-WISE (Wound and Impregnated Stacked Elastic tapes) conductor was studied to clarify its characteristics under certain magnetic fields. The WISE conductor, including 30-stacked REBCO (Rare-Earth Barium Copper Oxide) tapes, was fabricated and energized in a 9-T test facility which produced the condition of magnetic field B = 5 - 8 T and a temperature T = 30 - 50 K. Obtained critical currents (5.4 - 10.8 kA) increased with a decreasing magnetic field and/or temperature under the condition of $T > 40$ K. The maximum current of 16.9 kA was obtained at T = 30 K, which corresponded to the engineering current density j_{E} = 60 A/mm^2. Experimental results showed qualitative agreement with numerical calculations of the critical current. We confirmed the operation of the WISE conductor under a high magnetic field and low temperature.

Keywords: HTS, REBCO, helical fusion reactor, WISE

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1. Introduction

The High-Temperature Superconductor (HTS), reported by Müller and Bednorz in 1986, has the advantage of a higher critical temperature than that of the low-temperature superconductivity, which allows a wider range of operating temperatures, as well as a higher critical current value under high magnetic fields [1]. REBCO (Rare-Earth Barium Copper Oxide) is expected to be applied to fusion magnets because of its high mechanical rigidity, due to the use of Hastelloy as a substrate, and the low amount of silver which is beneficial to be used under neutron irradiation. The REBCO has a relatively large anisotropy, and the critical current characteristics are generally degraded when a magnetic field is applied in a direction perpendicular to the tape surface. When the REBCO tapes are stacked for making a cable, it is difficult to transfer the current to another tape stacked next to it because of the higher resistance substrate layer. Therefore, processing is required to geometrically replace the current path for current re-distribution under a time-varying operation. The Roebel conductors are stacked with tapes cut out in a meander shape to transpose the current path [2]. The CORC (Conductor on Round Core) conductor is made by wrapping multiple tapes, aiming at the average anisotropy of the conductor. The critical current value as a conductor is determined by the application of a magnetic field perpendicular to the tape, but the appeal of the CORC concept is its flexibility and allows for a small bending radius [3].

In order to apply HTS conductors to helical fusion reactors, it is important to clarify the current-carrying characteristics under high magnetic fields and low temperature conditions. Three types of HTS conductors with different concepts (STARS (Stacked Tapes Assembled in Rigid Structure) [4], FAIR (FSW, Al-alloy, Indirect-cooling, REBCO) [5], and WISE (Wound and Impregnated Stacked Elastic tapes) [6] have been studied in NIFS (National Institute for Fusion Science). Studying different types of conductors in a single institution brings the benefits of diversity to the study of HTS conductors. Among these three types of conductors, the WISE conductor, which has a relatively high degree of freedom in manufacturing, is studied. We assume the target helical reactor named FFHR-b3, which a coordinated design of the blanket and divertor is underway [7]. The major radius is R_{c} = 7.8 m and the toroidal magnetic field is B_{c} = 6.6 T. To obtain the magnetic field 6.6 T, a current of 52.1 kA flowing into two pairs of 570-turn helical coils is required. The cross-sectional area of the conductor is assumed to be 25 mm × 26 mm, so an engineering current density of 80 A/mm^2 is expected. The conductor includes the stacked HTS tapes, the cool-

author's e-mail: narushima.yoshiro@nifs.ac.jp
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ing pile, and the electromagnetic force support structure. It should be noted that the conductor studied here is dominated by the stacked HTS tapes whereas the conductor in the FFHR-b3 includes the cooling pipe, and the electromagnetic force support structure in addition to the stacked HTS tapes. In helical devices, which do not require a plasma current and confine the plasma only to the external magnetic field, a concerned AC loss is reduced because a significant change of the magnetic field like in tokamaks is not expected. Therefore, a simple stacked conductor is able to work. We fabricated a WISE conductor sample in the shape of a hairpin-like structure 4 m-long REBCO tape with 30 layers, folded with a radius of curvature of 35 mm (This is named WISE-U because its shape of a U-figure), and this was tested under the condition of magnetic field B = 5 T to 8 T and temperature T = 30 K to 50 K.

This article is composed as follows. The experimental setup, including the WISE conductor and test facility, is explained in the following section. Experimental results are shown in Section 3. We present a discussion in Section 4, prior to the summary in Section 5.

2. Experimental Setup

The overall shape of the WISE-U conductor is shown in Fig. 1. The total length of the WISE-U is about 2000 mm. The conductor jacket is made of aluminum with an outer/inner diameter of 19 mm/17 mm. The tip is a U-shaped stainless-steel pipe with a radius of curvature of R = 35 mm and an inner diameter of 19 mm. The end of the aluminum pipe was shaved slightly to reduce its outer diameter and inserted inside the U-shaped pipe. The U-shaped pipe structure allows the superconducting conductor section to be free of connections that contain normal-conducting resistance. Normally, when connecting two straight superconducting conductors, a normal-conducting connection is required, and connection resistance issues can arise. The current lead section is connected to a block of oxygen-free copper.

Thirty REBCO tapes (Shanghai Superconducting Technology Co., Ltd. 10 mm width, 65 μm thickness, and critical current I_c = 370 A @77 K, S. F.) are stacked and inserted into the stainless-steel coil tube (Fig. 2 (a)). The tapes were made in pairs with the superconducting surfaces in contact with each other, which is capable of current transposition. The stainless-steel coil tube, including the stacked HTS tapes, is inserted into the U-shaped stainless-steel pipe with the curvature radius of R = 35 mm (Fig. 2 (b)). In this process, extensive stress is not applied to HTS tapes. The remaining part, which will be straight, is inserted into the aluminum pipe prior to the connection of the aluminum pipe and the U-shaped pipe. The pipe is fixed to the FRP (Fiber Reinforced Plastics) support plate (Fig. 3 (a)), and the entire pipe is heated up to about 100°C in a vertically standing position and impregnated with a low-melting-point metal U-Alloy 60 (Fig. 3 (b)). The U-Alloy 60 has the melting point of 60°C, and the weight composition is In 51wt%, Bi 32.5%, and Sn 16.5%.

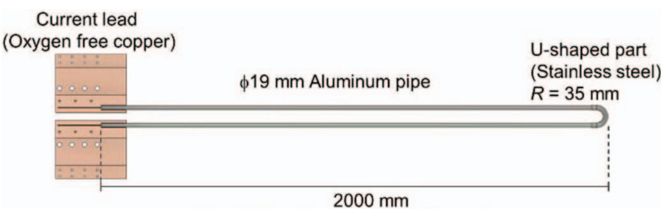

Fig. 1 Overview of WISE-U conductor.

The current lead terminal is fabricated by cutting out a block of oxygen-free copper with a size of about 100 mm × 200 mm × 300 mm (Fig. 4 (a)). Aluminum pipes are placed in the thick grooves, and stacked HTS tapes are inserted in the thin grooves (Fig. 4 (b)). The low-melting-point metal, U-Alloy 60, is poured into these grooves to electrically bond the current-introduction terminal and the HTS tape (Fig. 4 (c)). At the same time, the superconducting part and the current-introduction terminal can be fixed. In the previous WISE experiment [6], the current introduction terminal was fabricated by fixing 10 HTS tapes by the crimping method using indium foil, which is shown in Fig. 2 of Ref. [6]. On the other hand, the crimping method using indium foil is not adopted here, and torque control is not required.

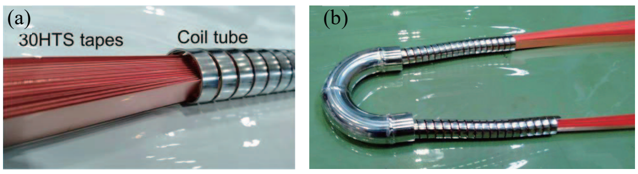

Fig. 2 (a) Thirty stacked REBCO tapes inserted in coil tube. (b) Insertion of stacked tapes into U-shaped stainless steel pipe.

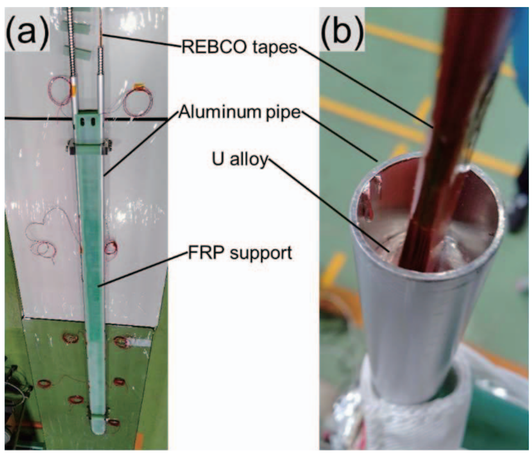

Fig. 3 (a) Pipe structure is fixed to PRF support board. (b) Low point melting metal is impregnated.

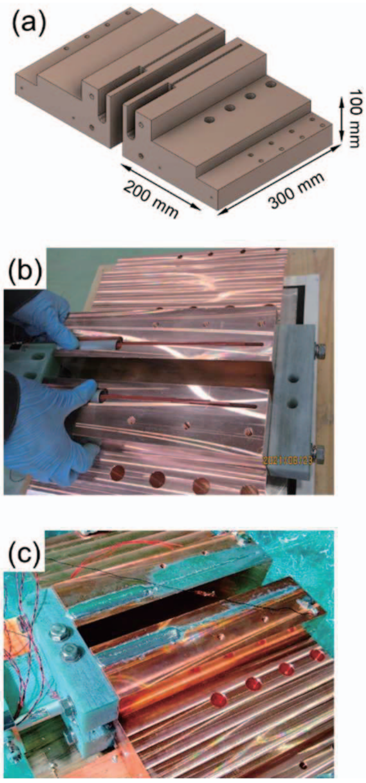

Fig. 4 (a) Current leads machined from block of oxygen-free copper. (b) HTS conductor parts are slipped into groove. (c) Low melting point metal impregnated into groove.

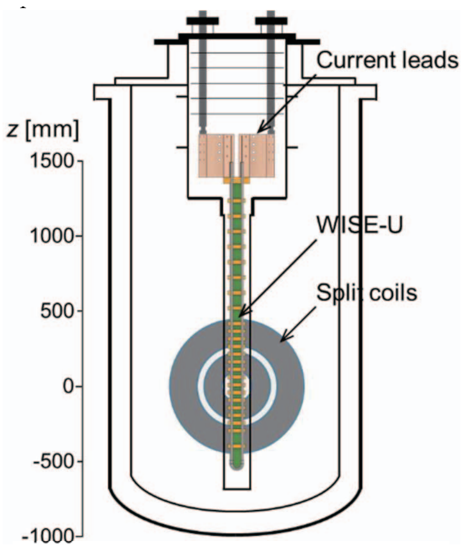

Fig. 5 Test facility and inserted WISE-U conductor.

The test facility shown in Fig. 5 is able to obtain temperatures up to $T = 4$ K with liquid/gas helium. A split coil consisting of two pairs of circular coils, one with an outer diameter of 893 mm and an inner diameter of 536 mm and the other with ϕ 442 mm o.d. and ϕ 200 mm i.d., can generate a magnetic field up to $B = 9$ T. The direction of the magnetic field is orthogonal to the plane. When the

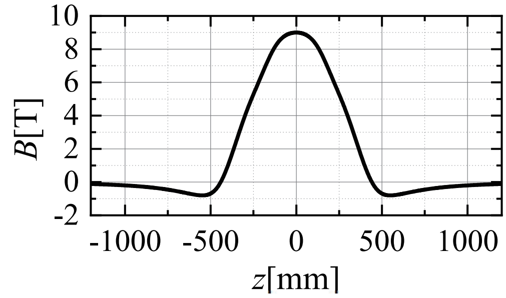

Fig. 6 Profile of magnetic field produced by split coil in 9 T facility.

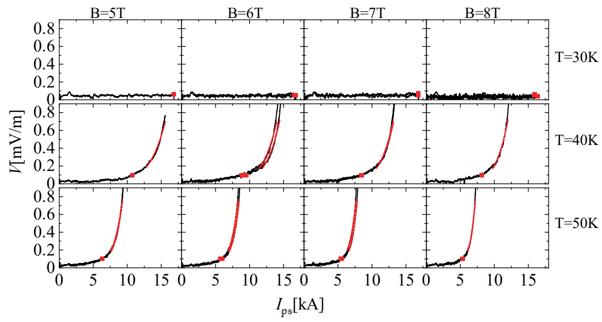

Fig. 7 *I*-*V* curves for all temperature and magnetic field conditions.

WISE-U is installed in the test facility, the direction of the magnetic field is parallel to the HTS tape; the current in the WISE-U flows counterclockwise on the paper, and the electromagnetic force is totally applied to the inward direction of the WISE-U conductor. Hereafter, the current flowing in WISE-U is indicated by I_{ps}. The profile of the magnetic field produced by the split coils is shown in Fig. 6, where the magnetic field is more than 80% of the maximum field within $z = \pm 170$ mm from the center, and is zero at $z = \pm 440$ mm.

3. Experimental Results

For the energization test of the WISE-U, the temperature was decreased in the order of $T = 50$ K, 40 K, and 30 K. At each temperature, the magnetic field was decreased in the order of $B = 8$ T, 7 T, 6 T, and 5 T. One or two energizations were carried out under each condition. The *I*-*V* curves of all energizations are shown in Fig. 7. The vertical axis V indicates the voltage at $z = 0$ where the externally imposed magnetic field is maximum. Red dots indicate the position of the voltage 0.1 mV/m and the red line shows the power-law fitting curve leading to the n-value. The critical current values were obtained for $T = 40$ K and 50 K, in which the current flowing in the WISE-U was interrupted immediately after a quench-detector worked to enable the avoidance of damage. Squares indicate the critical current I_c. Meanwhile, under the condition of $T = 30$ K, the quench-detector working prior to the cur-

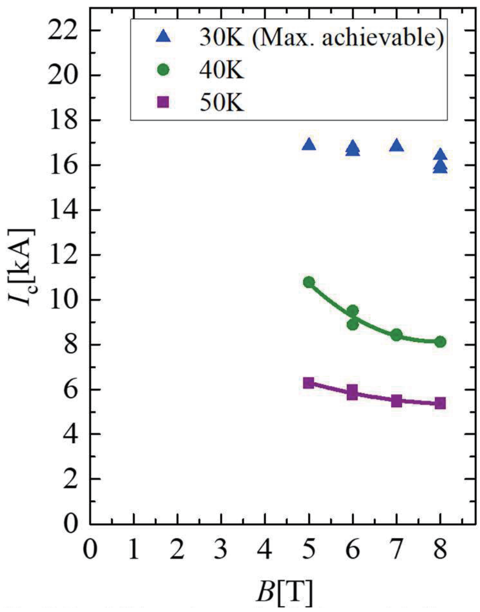

Fig. 8 B and T dependence of critical current I_c. Square and circles are I_c in T = 50 K and 40 K, respectively. Triangles show maximum reached current in T = 30 K condition.

Table 1 Critical current values of WISE-U conductor.

	I_c [kA]			
T [K] \ B[T]	5	6	7	8
40	10.8	9.2	8.4	8.1
50	6.3	5.9	5.5	5.4

rent did not reach a critical current. Therefore, the critical current was not obtained but the maximum current was. Squares indicate the maximum current I_{max}. The fitting curve is reminiscent of a low n-value; details of the n-value will be discussed later. The magnetic field and temperature dependence of the critical current value are shown in Fig. 8. It should be noted that the experimental data at T = 30 K, indicated by triangles, do not represent the critical current but the maximum achievable current. At T = 50 K (squares), the critical currents of I_c = 5.4 kA (B = 8 T) to I_c = 6.3 kA (B = 5 T) were obtained, and I_c = 8.1 kA (B = 8 T) to I_c = 10.8 kA (B = 5 T) were obtained at the lower temperature T = 40 K. These critical current values are summarized in Table 1. The maximum current of 16.9 kA was obtained at T = 30 K and B = 5 T, which corresponded to the engineering current density of j_E = 60 A/mm^2 for cross section of 19 mm o.d. aluminum pipe.

The evolution of n-values with respect to the number of energizations including all conditions is shown in Fig. 9. From the 1st to the 8th energization (T = 50 K), the n-value gradually decreased from n = 8.6 to 6.9. Consequently, at T = 40 K, the n-value was maintained at around 6.8 from the 9th to 14th energization. These values are lower than the typical values of the HTS; the CORC and FAIR conductors have obtained n = 10.3 [3] and n = 21 [5], respectively.

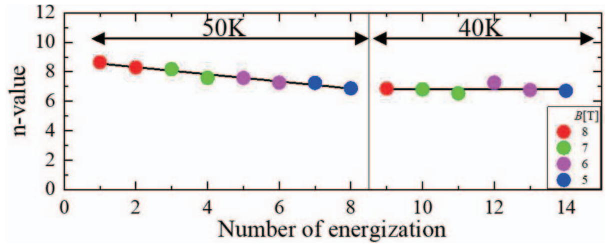

Fig. 9 Trend of n-value on number of energizations.

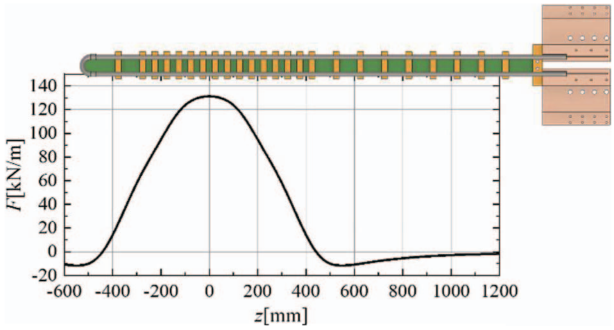

Fig. 10 Profile of electromagnetic force for B = 8 T and I_{ps} = 16.4 kA. The figure of WISE-U conductor is shown as reference.

The inward electromagnetic force was mainly applied to the WISE-U conductor energized in the magnetic field. At T = 30 K, I_{ps} = 16.4 kA was energized at B = 8 T, so the WISE-U conductor experienced an electromagnetic force of F = 131 kN/m. Near the center of the split coil, the force per 100 mm amounted to 13.1 kN, which is about 1.3 gravitational tons of force per 100 mm. However, the force was sufficiently supported by the FRP support plate, so there was no damage to the conductor due to the electromagnetic force. Figure 10 shows the stress distribution. From the center of the coil (z = 0) to $|z|$ = 440 mm, the electromagnetic force decreased from 131 kN/m to 0, which corresponded to the inward force on the WISE-U conductor. At $|z|$ > 440 mm, a negative electromagnetic force, i.e., the outward force appeared. The maximum inward force of $|-11.7|$ kN/m was applied at $|z|$ = 550 mm. This outward force was retained by the support hardware, which could prevent the outward bending of the WISE conductor.

4. Discussion

The WISE-U conductor studied here does not require a normal conductor connection at the tip, as shown in Fig. 1 and Fig. 2 (b), which is able to eliminate Joule heating. Eliminating the normal conducting structure as much as possible is an advantage of the flexibility of the WISE conductor for fabrication. The fabrication of current leads of the WISE-U conductor adopts the same method as low-melting-point metal impregnation of the superconducting conductor part, as shown in Fig. 4. Therefore, crimp torque control and indium foil to ensure sufficient current flow between HTS tape and the current lead are not required, which allows easy fabrication. Detailed studies on the structure of current leads will be important in the future, along with that on the connection technology of the HTS tape [8].

Critical current values were obtained at $T = 40$ and 50 K and $B = 5$, 6, 7, and 8 T as shown in Table 1. The I_c increased as B and/or T decreased, which confirmed that the WISE-U worked as a typical superconductor. Under the condition of $T = 30$ K and $B = 5$ T, the maximum current $I_{max} = 16.9$ kA was obtained, which corresponded to the maximum engineering current density $j_E = 60$ A/mm^2 which was still smaller than the target value of $j_E = 80$ A/mm^2. Increasing the number of HTS tapes, the j_E could rise because there was still space inside the coil tube.

The obtained n-values are generally smaller than those of HTS conductors, which is not yet clear whether the reason for this is due to the manufacturing process or the initial cooling or energization. The decreasing of the n-value was observed up to 8th energization, as shown in Fig. 9, which implied a degradation of the WISE-U conductor due to micro displacement by the electromagnetic force. After the 9th, the n-value maintained almost constant value, which seems to indicate that the condition of the WISE-U conductor may have settled down. To make the degradation behavior clearer, multi energization cycles have to be investigated.

The WISE-U conductor was not mechanically destroyed even though the maximum experienced electromagnetic force reached 131 kN/m, as shown in Fig. 10, which proved the robustness of the WISE-U conductor. Considering with reference to the exact electromagnetic force calculation in FFHR-d1A [9], the magnetic field directly under the helical coil of the FFHR-b3 can be assumed to be 17 T. In this condition, the electromagnetic force on a single conductor flowing at 52 kA is estimated to be about 880 kN/m. The value obtained in the experiment is lower than that, so future research on counter electromagnetic force is needed. In real conditions of a fusion reactor, there can be various magnetic field angles and strengths, so that a more detailed study is required.

The characteristics of critical current values obtained for the WISE-U conductor were compared with analytical calculations of the critical current values. In the calculation, the HTS conductor was divided into sufficiently small elements and the current flowing in the elements was assumed [10, 11].

Initially, the critical current of each element was calculated under the conditions of a self-magnetic field, external coil field, and temperature. Iterative calculations were performed, increasing the current little by little until the current of all the elements matched the critical current. The algorithm of the analysis is shown in Fig. 11. In this calculation, the current transfer between each tape was assumed. (1) Input the initial value of the element current. (2) Calculate the self-magnetic field produced by the element current. (3) Calculate the critical current under conditions of the temperature and magnetic field. (4) Compare the element current and the critical current, and if the critical current is larger than the element current, (5) the incremented current is added to the element current and goes to (2). If the element current is larger than the critical current, (6) that difference between the element current and the critical current is distributed to the other elements that have not reached the critical current. (7) Compare the total element current and the total critical current. If the former is smaller than the latter, go to (5). Otherwise, the total element current is taken as the whole critical current value of the conductor. Here, the data of the critical current depending on the magnetic field has been directly provided by the Shanghai Superconducting Technology Co., Ltd. Figure 12 shows the results of the numerical calculation (solid lines) and the experimental results (symbols). The calculated critical current values are $I_c = 7.2$ kA ($T = 50$ K), 12 kA (40 K), and 17.8 kA (30 K) at $B = 6$ T. The calculated critical current value decreases with an increasing magnetic field and temperature. In this analysis, the critical current is obtained when the magnetic field is perpendicular to the HTS tape, so the calculated results are

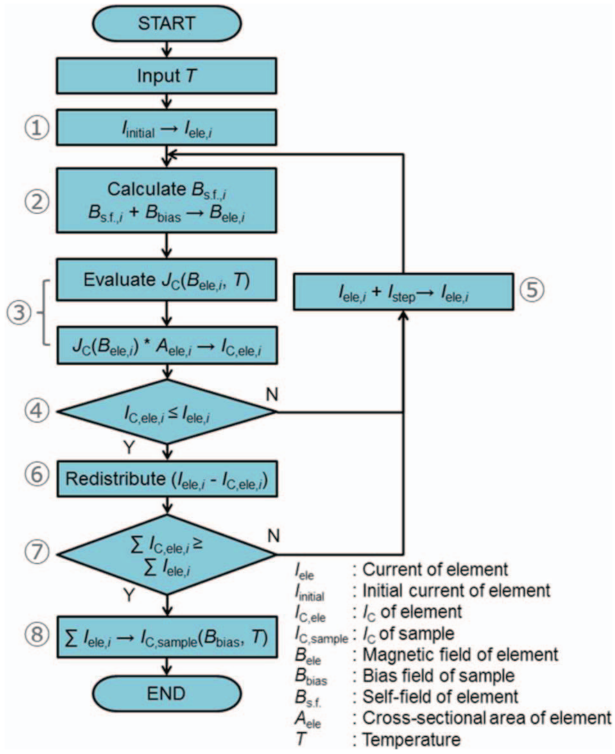

Fig. 11 Flowchart of critical current value analysis.

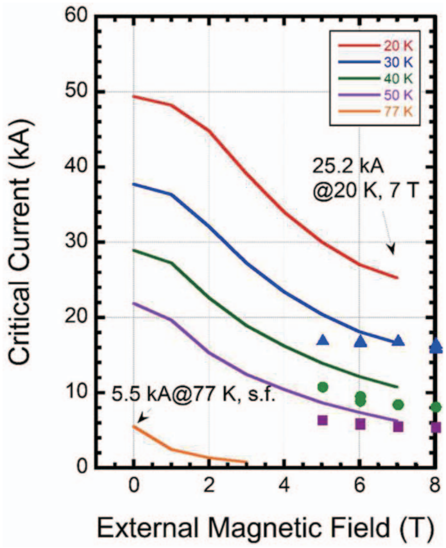

Fig. 12 Numerical calculation (Solid lines) of critical current of WISE-U conductor with experimental results (dots). Solid lines of red, blue, green, purple, and orange indicate 20 K, 30 K, 40 K, 50 K, and 77 K, respectively. Triangles, circles, and squares indicate experimental data in 30 K, 40 K, and 50 K, respectively.

considered to correspond to the lower limit of the experimentally obtained critical current. The experimental critical current value at $T = 50$ K is quantitatively close to the calculated result, while the experimental result at $T = 40$ K is lower than the calculated I_c. It should be noted that the experimental data of currents at $T = 30$ K do not represent the critical current but the maximum achievable current. Overall, the experimental and numerical results are qualitatively consistent. It is necessary to improve the accuracy of the numerical calculation in the future. We also plan to conduct experiments to obtain the critical current value at lower temperatures.

5. Summary

The HTS WISE-U conductor was fabricated, and its characteristics were investigated in the magnetic field. The energized tests were carried out at $T = 30$ to 50 K, and critical current values of $I_c = 5.4$ to 10.8 kA were obtained. Under $T = 30$ K, $B = 5$ T conditions, the quench detector worked when the current was energized to $I_{ps} = 17$ kA (current density is 60 A/mm^2) before reaching the critical current value. Fortunately, the superconducting part was healthy. As a result of comparison with numerical calculations, the critical current values obtained in the experiment were qualitatively consistent. Descending and maintenance of the n-value were observed. Multi energization cycles test has to be investigated to make the degradation behavior clearer.

In the future, it is necessary to obtain the critical current values at lower temperatures by using more detailed numerical calculations, based on experimental conditions.

Acknowledgement

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