HIGH-TEMPERATURE SUPERCONDUCTING MAGNET SYSTEM FOR THE NEXT-GENERATION HELICAL DEVICE

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Abstract

The High-Temperature Superconducting (HTS) magnet is being considered to apply to the next-generation helical experimental device. Three types of large-current (4-18 kA) HTS conductors are being developed. One of the crucial requirements is to secure the high current density of 80 A/mm^2 at a condition of 20 K temperature and 10 T magnetic field. In the first phase of the development, short samples of each conductor have been fabricated and tested in liquid nitrogen at 77 K with no external magnetic field. The critical current was observed and compared with expectation. The fabrication methods have been improved to satisfy the magnet requirement. The winding method and quench protection are also crucial requirements to use the conductor in the magnet, which are being examined with different scenarios for the three conductor options.

1. INTRODUCTION

Along with the successful plasma experiments for confining high-density and high-temperature plasmas in the Large Helical Device (LHD) at National Institute for Fusion Science (NIFS), the design studies for the helical fusion reactor FFHR have progressed with more than 25 years of intensive research. In the recent design of FFHR-d1, it was decided to employ the High-Temperature Superconducting (HTS) magnet as the primary option [1], and a 100-kA-class HTS conductor has been developed [2]. It is noted that large-current capacity HTS conductors are being developed also in the world to be applied to a variety of designs of fusion reactors, such as reviewed in [3] and a recent report by [4]. The advantages of HTS are found that it is used up to high magnetic field of >16 T and at elevated temperature operation of > 10 K, both of which are clear comparisons to the well-established Low-Temperature Superconducting (LTS) conductors and magnets. As a prior phase before applying to the fusion reactor, it is now being examined whether the HTS magnet can be applied to the next generation helical experimental device. For this purpose, a relatively smaller conductor is required, and presently, the target is found at 4-18 kA current in the magnetic field of 10 T and at temperature of 20 K. For this purpose, three types of HTS conductors with different internal configuration are being developed.

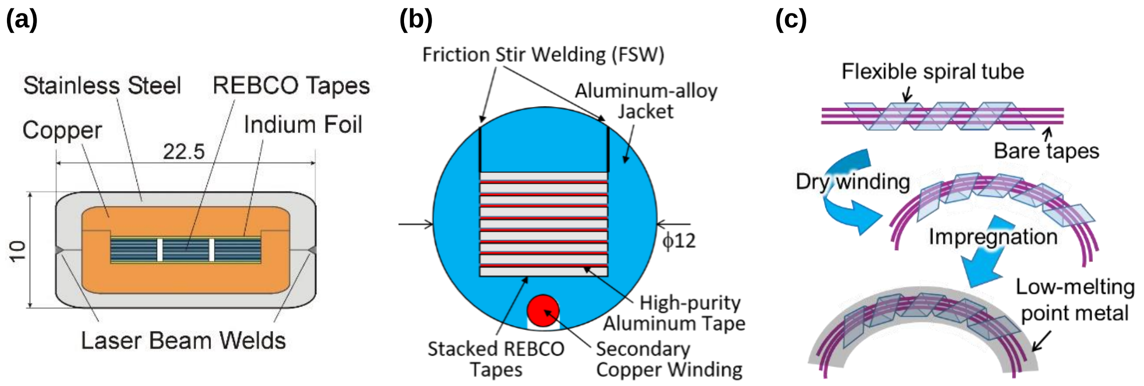

FIG. 1. Schematic drawings of three types of large-current HTS conductors being developed to apply to the next-generation helical device: (a) STARS, (b) FAIR, and (c) WISE conductor.

2. THREE TYPES OF HTS CONDUCTORS

Presently, three types of HTS conductors are being developed at NIFS. The conductors are named "STARS" for Stacked Tapes Assembled in Rigid Structure, "FAIR" for Friction Stir Welding (FSW), Aluminum-alloy jacket, Indirect cooling, REBCO, and "WISE" for Wound and Impregnated Stacked Elastic tapes. Illustrative images of these conductors are depicted in Fig. 1, and the major specifications of them are summarized in Table 1. The basic features of the three conductors are described in the following.

TABLE 1. MAJOR SPECIFICATIONS OF THE THREE TYPES OF HTS CONDUCTORS

	STARS	FAIR	WISE
Size (w/o. insulation)	10 mm × 22.5 mm	ϕ12 mm	7.2 mm × 7.2 mm
Current @10 T, 20 K	18 kA	12.5 kA	4 kA
Current density	80 A/mm^2	110 A/mm^2	80 A/mm^2
HTS material	REBCO	REBCO	REBCO / Bi-2223
Twisting	none	2 rotations / m	none
Stabilizer	Cu	Al-alloy	U-Alloy78
Reinforcement	SS	Al-alloy	SS (partially)
Welding	LBW	FSW	none
Electrical Insulator	internal	external	none (NI)
Impregnation	none	Epoxy	U-Alloy78
Joint	Mechanical	Solder	U-Alloy78
Quench protection	Resistive dump	Resistive dump w/ secondary circuit	Self-protection by NI winding
Helical coil winding	Joint-winding	Continuous winding	Continuous winding

In the above, SS: stainless-steel, LBW: laser beam welding, FSW: Friction Stir Welding, and NI: Non-Insulation.

2.1. STARS conductor

The STARS conductor has been developed to be applied to the future helical fusion reactor FFHR-d1 as a long term project. In this conductor, REBCO HTS tapes are simply stacked and imbedded in a copper stabilizer. The outer jacket is made of stainless-steel for mechanical reinforcement. A prototype sample of the STARS conductor was fabricated in 2013 and it achieved 100 kA at 20 K and 5.3 T [2]. It is considered that this prototype tests have proven the basic feasibility of the concept of simple stacking of HTS tapes. It is noted that the discussion continues whether simple stacking may really work for conductors used in large-scale magnets. Increase of AC losses and formation of non-uniform current distribution among HTS tapes are the two major concerns for this concept with a lack of twisting and transposition. It has been found that the AC losses are not significantly different from the case having twisting and transposition of REBCO tapes [5]. The non-uniform current distribution is a big problem for LTS conductors, which degrades the cryogenic stability. However, due to the orders of higher stability margin of HTS, the non-uniform current distribution may not become a very serious problem, as was confirmed in a simple experiment using five-layered stack of REBCO tapes and current feeding with intentionally provided non-uniform current distribution [6]. Having the simple stacking of HTS tapes provides many advantages, such that the conductor is mechanically robust without having a weak point. It is also cost effective because of the simple structure. Furthermore, the joint between conductors could be made rather easily by employing a mechanical bridge-type lap joint. This joint technique has been successfully developed in Tohoku Univ. [7]. In the present phase of the development of the STARS conductor to be applied to the next-generation helical experimental device, a scaled-down conductor with a 18-kA operation current (Fig. 1(a)) is presently designed and developed. Though the proto-type 100-kA conductor was fabricated with the stainless-steel jacket sustained by bolts, the present conductor employs laser beam welding (LBW) to seal the stainless-steel jacket. An initial testing of the laser beam welding confirmed that the maximum temperature observed during the welding was limited by ~44 degrees centigrade, which was well below the specified limit of 200 degrees centigrade for REBCO tapes. A 3-m-long straight conductor sample was fabricated as shown in Fig. 2. It should be noted that the original design of the STARS conductor has an internal electrical insulation between the copper stabilizer and the stainless-steel jacket. This time, the internal electrical insulation was omitted as the first trial.

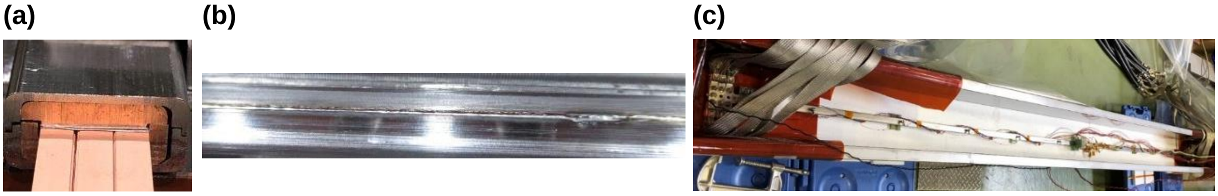

FIG. 2. Photographs of the fabricated STARS conductor: (a) cross-section of an end section before attaching a current-feeder terminal, (b) laser welded splice of the stainless-steel jacket, and (c) entire sample installed in a container for liquid nitrogen cooling.

2.2. FAIR conductor

The FAIR conductor (illustrated in Fig. 1(b)) has a stack of REBCO tapes imbedded in a circular aluminum-alloy jacket. The aluminum-alloy jacket is sealed by applying the FSW technique [8]. Due to the softness of the aluminum-alloy (before heat treatment), a slight twisting (2 rotations per meter) is included for the purpose of securing uniform current distribution among REBCO tapes. The conductor cross-section and a 1-m-long prototype sample is shown in Fig. 3(a). A series of 1-m conductors have been tested by forming a sample structure shown in Fig. 3(b), and immersed in liquid nitrogen using the cryostat shown in Fig. 3(c).

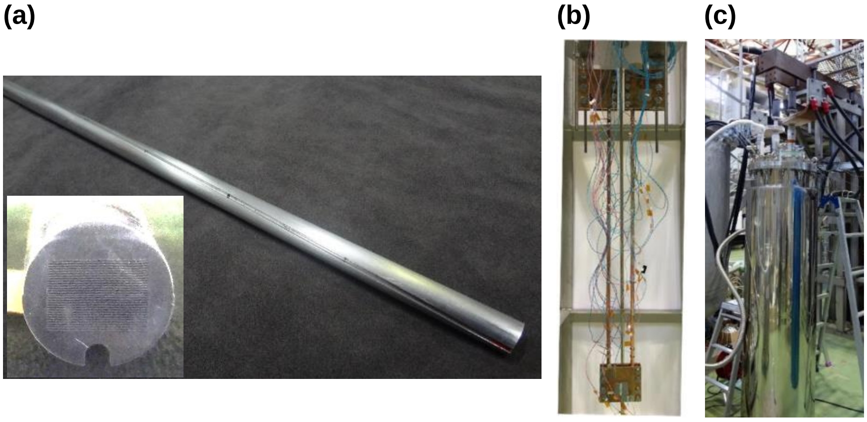

FIG. 3. Photographs of the fabricated FAIR conductor: (a) cross-section and a 1-m long conductor (twisted FSW splice is seen), (b) a sample made of two FAIR conductors to be tested in liquid nitrogen, and (c) facility for liquid nitrogen testing.

2.3. WISE conductor

The WISE conductor (illustrated in Fig. 1(c)) is formed by inserting a stack of REBCO tapes into a flexible metal tube, and the winding package of a coil is impregnated with low-melting point metal alloy “U-Alloy78” (melting point: ~78.8 degrees centigrade) after completing the winding process [9]. As the first trial for making a WISE conductor and its winding, a small solenoid coil was fabricated, such as shown in Fig. 4(a). In liquid nitrogen, a 0.16 T magnetic field was produced at the center of the coil with a 800 A conductor current. Although normal-transitions were observed from some tapes, the coil was stably excited. A small helical coil was also fabricated by winding the WISE conductor into a helical coil-can which was fabricated by additive manufacturing. A series of 1-m long WISE conductors have been fabricated by inserting REBCO tapes surrounded by a stainless-steel tube into an aluminum-alloy pipe, such as shown in Fig. 4(b).

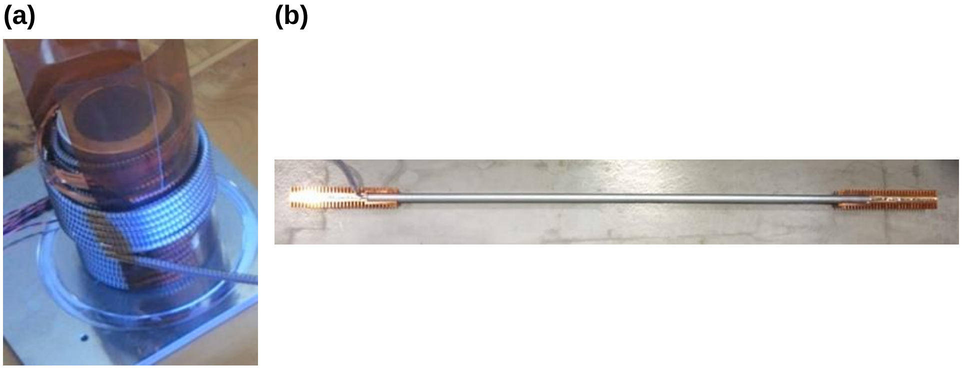

FIG. 4. Photographs of (a) a solenoid coil wound with a WISE conductor and (b) a straight 1-m long sample of a WISE conductor imbedded in an aluminum pipe.

3. TESTS OF THREE-TYPES OF HTS CONDUCTORS IN LIQUID NITROGEN

3.1. STARS conductor

Tests of the 3-m long STARS conductor sample were carried out in liquid nitrogen with a setup shown in Fig. 2(c). A typical example of the critical current measurement is shown in Fig. 5(a) where the observed voltage along the sample is plotted as a function of the sample current. In this case, the critical current was evaluated as 3,950 A. The observed critical current is found to roughly match the estimated value by taking account of the spatial distribution of the current density and produced magnetic field by applying the calculation method developed for analysing the former 100-kA conductor [10]. The critical current characteristics for a single REBCO tape is interpolated depending on the applied magnetic field strength and its orientation. The critical current measurements were repeated multiple times by having thermal cycles (warming up the sample and cooling down again). The trend of the observed critical current is shown in Fig. 5(b) as a function of the cooling cycle. It was observed that the critical current degraded by ~1% in the second cooling cycle. The reason is not clear so far. During these tests, the sample was also bent with a bending radius of 3,000 mm. With this condition the critical current was decreased by ~1%. It was estimated that a tensile strain of about 0.1% was applied because the neutral line for this bending was located at the bottom of the conductor cross-section where the surface of the conductor touched the surface of a stainless-steel jig having the radius of 3,000 mm. Releasing the support jig, it was observed that the critical current recovered almost back to the original value before bending. This observation could be explained by the characteristics of a single REBCO tape against tensile strain. After having completed the present tests in liquid nitrogen with no external magnetic field, short samples will be tested in the superconductor testing facilities under high magnetic field (>7 T) and cryogenic temperature (4-50 K).

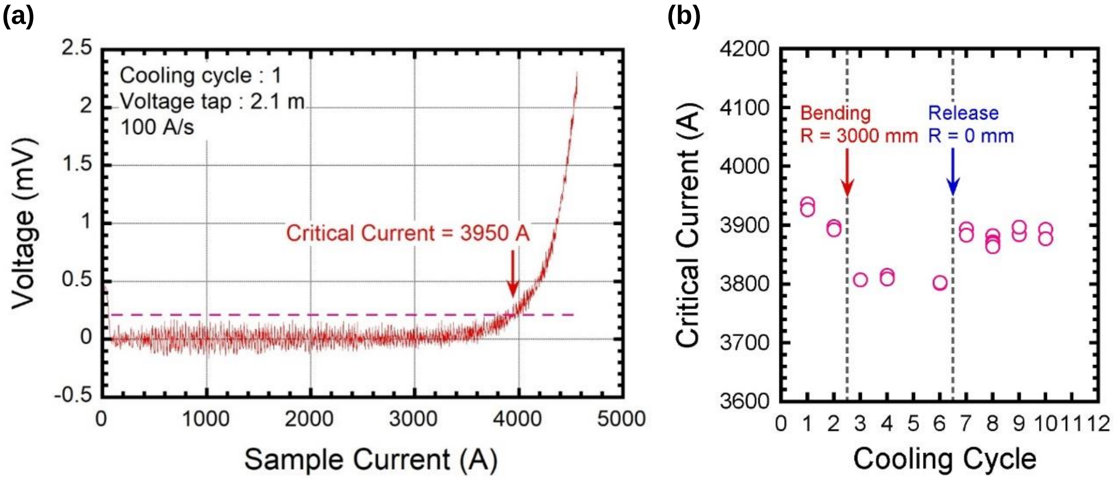

FIG. 5. (a) Example of the critical current measurement for the STARS conductor: voltage along the sample versus the current. (b) Trend of the measured critical current on the cooling cycle.

3.2. FAIR conductor

A series of 1-m-long prototype samples of the FAIR conductor have been fabricated and tested at 77 K, 0 T. Though some degradation was initially observed with the measured critical current by cyclic excitations, steady improvement is foreseen by optimizing the fabrication process, as is shown in Fig. 6. The optimization has been incorporated by adjusting the suitable size of the tip for the FSW process. When the conductor is cooled down to the liquid nitrogen temperature (77 K) from the FSW temperature (~473 K), owing to the difference in the thermal contraction between the aluminum-alloy jacket and REBCO tapes (-0.4 %), an excessive shear strain (buckling) might be applied locally to the REBCO tapes. By adjusting the process to secure a uniform FSW in in the longitudinal direction, it was confirmed by experiments that the critical current degradation did not occur in REBCO tapes during the conductor production, including twisting, and thermal cycling. By further quantitatively evaluating the cause of the REBCO conductor degradation, it has been determined that stable fabrication of the FAIR conductor without a critical current degradation is possible. After having completed the present tests in liquid nitrogen with no external magnetic field, short samples will be tested in the superconductor testing facilities under high magnetic field (>7 T) and cryogenic temperature (4-50 K).

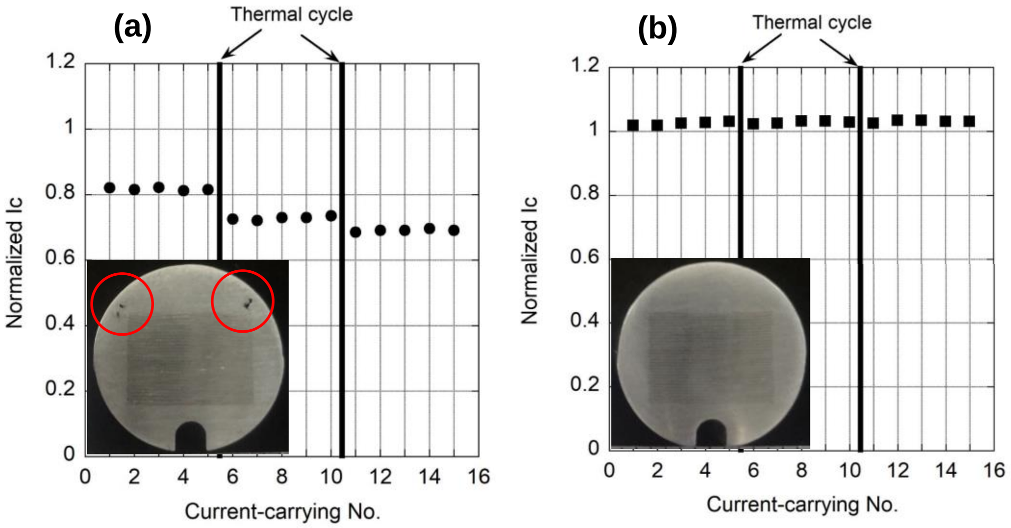

FIG. 6. Dependence of the measured critical current (normalized by the expected value from the single-tape property) of the FAIR conductor on the current-carrying number (up to 15 times including 2 thermal cycles) for (a) before and (b) after an optimization of the fabrication process. The tested conductor samples used limited number of REBCO tapes compared to the final specification. Photos of the cross-section of the conductor are also shown for each case. Note that cracks observed at two locations (indicated by circles) above the REBCO tape stack in the aluminium-alloy jacket in (a) disappeared in (b).

3.3. WISE conductor

A series of 1-m long WISE conductor samples were fabricated and tested in liquid nitrogen. At the beginning of the fabrication, considerable degradation of the critical current was observed with cyclic operations and thermal cycles. A possible reason for this degradation is delamination of the superconducting films from the REBCO tapes, which might be brought about by the difference of thermal contractions between REBCO tapes and low-melting temperature metal. This might be a similar phenomenon that was observed in many REBCO coils impregnated by epoxy resin showing degradation of the critical current due to the delamination of REBCO superconducting films due to the difference of thermal contractions between the REBCO tapes and epoxy resin. In order to solve this problem, it was invented for the WISE conductor to use BCCCO (Bi-2223) tapes in the outer sides of a stack of REBCO tapes. Then improvement was confirmed, and the voltage generation of the new conductor is shown in Fig. 7. After having completed the present tests in liquid nitrogen with no external magnetic field, short samples will be tested in the superconductor testing facilities under high magnetic field (>7 T) and cryogenic temperature (4-50 K).

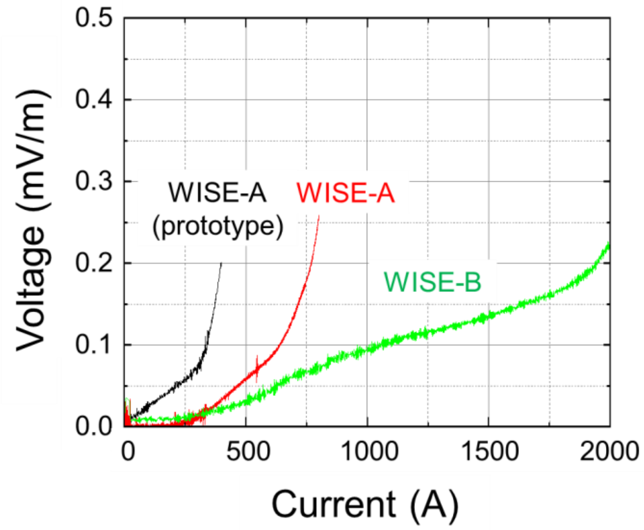

FIG. 7. Critical current measurement of WISE conductors. The measured voltage (normalized for a unit length) is plotted as a function of the sample current. The WISE-A conductor includes 6 REBCO tapes and two BSCCO tapes, whereas the WISE-B uses 22 REBCO tapes and 2 BSCCO tapes.

4. COIL WINDING METHOD AND QUENCH PROTECTION

The winding procedure for coils and the quench protection method are both crucial issues for the HTS conductors and magnets. Each of the three types of HTS conductors being developed here employs its own winding procedure and quench protection method.

For the STARS conductor, the winding procedure of the helical coils is to employ the “joint-winding” rather than using the continuous winding method. For the joint-winding, a bridge-type mechanical lap joint technique has been developed by Tohoku Univ. and the recent progress shows that a low joint resistivity of ~3 pΩm^2 can be achieved [7]. It is also estimated that a fast onsite winding is possible with parallel works [11]. By having a flattened structure of the conductor cross-section, the helical winding property is supposed to be not very different from that of the NbTi/Cu conductor used for the present LHD, despite the enhanced mechanical strength using stainless-steel. The edgewise strain can be minimized to be almost zero by adjusting the inclination angle of the conductor in the winding package [12]. Regarding the quench protection, the STARS conductor employs the conventional dump resistor method. A crude estimation with a zero-dimensional model gives a required discharging time constant, as shown in Fig. 7, as a function of the allowable hot-spot temperature by varying the current density. For a current density of 25 A/mm^2, a relatively long discharging time constant of 30 s may allow a hot-spot temperature of < 200 K. This is a similar result that was found with a one-dimensional simulation for a 100-kA conductor model using a Finite Element Method (FEM) [13]. On the contrary, for a high current density of 80 A/mm^2, it is found that a fast discharging time constant of <3 s is required to limit the hot-spot temperature to <200 K. An FEM analysis is ongoing to make a more precise analysis.

For the FAIR conductor, the winding of the helical coils can be done by the conventional continuous winding method, such as employed in the present LHD as well as for the LTS option of the helical reactor [14]. Regarding the quench protection, a secondary loop method is utilized to enhance the normal-zone propagation to limit the hot-spot temperature, because the aluminum-alloy used in the FAIR conductor possesses less heat capacity than that of the stainless-steel jacket in the STARS conductor. For the secondary loop, a copper wire is imbedded in the FAIR conductor, as shown in Fig. 1(b), to be used as a heater. The feasibility of this option is being examined through numerical simulations, and it is shown that the hot-spot temperature is limited by <310 K with a discharging time constant of 2.65 s accompanied with a secondary loop [15].

The advantage of the WISE conductor is found in its flexibility. The HTS tapes are surrounded by a metal spring and thus the conductor is soft during the winding process of a coil, which might be effective for facilitating the winding process of helical coils. After the winding, the coil package is impregnated by low-melting temperature metal for mechanical reinforcement. In order to increase the mechanical rigidity, discrete stainless-steel jacket could be attached [16]. It should be noted that between turns of WISE conductors, there is no electrical insulation, which corresponds to the Non-Insulation (NI) coil winding. The NI coil is supposed to have a self-protection capability [17]. The feasibility of this idea is being examined through small-coil experiments and numerical simulations such as done in [18]. The results will be described elsewhere.

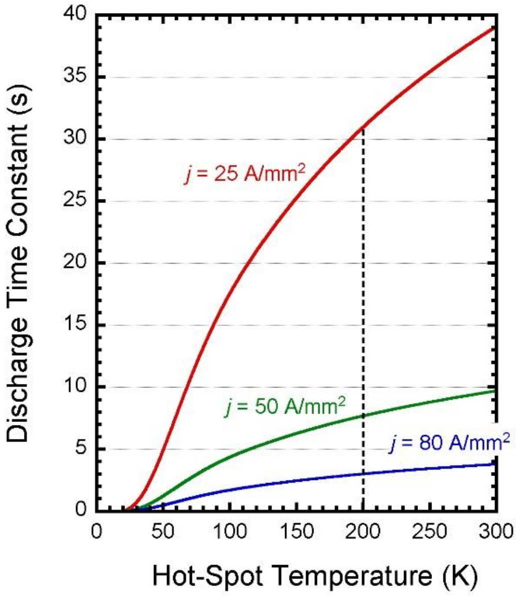

FIG. 8. Required discharging time constant versus the allowable hot-spot temperature evaluated for the STARS conductor with current density j of 25, 50, and 80 A/mm^2.

5. SUMMARY

Large-current capacity HTS conductors are being developed with three different configurations to be applied to the next-generation helical fusion experimental device. The conductor samples were fabricated and tested in liquid nitrogen with no external magnetic field. In the next phase of the development, short samples will be tested in the superconductor testing facilities under high magnetic field of >7 T and cryogenic temperature of 4-50 K with helium gas cooling. By carrying out this test, some suitable conductors will be selected to go into the next phase of the conductor development with >10-m length.

ACKNOWLEDGEMENTS

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