Progress of HTS STARS Conductor Development for the Next-Generation Helical Fusion Experimental Device*)

Nagato YANAGI[1,2], Yoshiro TERAZAKI[1], Yoshiro NARUSHIMA[1,2], Yuta ONODERA[1], Naoki HIRANO[1], Shinji HAMAGUCHI[1,2], Hirotaka CHIKARAISHI[1], Suguru TAKADA[1,2], Satoshi ITO[3] and Kazuya TAKAHATA[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*
[3] *Tohoku University, 6-6-01-2 Aramaki-Aza-Aoba, Aoba-ku, Sendai, Miyagi 982-8579, Japan*

(Received 10 January 2022 / Accepted 25 April 2022)

A High-Temperature Superconducting (HTS) magnet is being considered to for use in the next-generation helical experimental devices. Three types of large-current HTS conductors are being developed, and one of them is the STARS (Stacked Tapes Assembled in Rigid Structure) conductor which uses HTS tapes with a simple stacking technique. Following the proof-of-principle experimental results obtained in the former 100-kA-class prototype hand-made conductor sample, an actually applicable conductor is being developed with a rated current of 18 kA at a temperature of 20 K and a magnetic field of ~10 T. One of the crucial requirements for this conductor is to have a high current density of 80 A/mm^2. In the first phase of the development, a 3-m short sample was fabricated by applying laser-beam welding to the stainless-steel jacket. It was tested in liquid nitrogen at 77 K with no external magnetic field. Then the sample was tested in gaseous helium at 20 - 40 K under a magnetic field of 6 - 8 T, and the results show that the basic requirements were satisfied.

© *2022 The Japan Society of Plasma Science and Nuclear Fusion Research*

Keywords: high-temperature superconductor (HTS), REBCO, STARS, helical fusion reactor, FFHR

DOI: 10.1585/pfr.17.2405076

1. Introduction

A large-current High-Temperature Superconducting (HTS) conductor is a candidate to be used with future fusion reactor magnets. At the National Institute for Fusion Science (NIFS), the development of such an HTS conductor has been progressing since 2005 to use in the helical fusion reactor FFHR [1–3]. It is noted that large-current capacity HTS conductors are being developed also in the world to be used in a variety of designs of fusion reactor magnets, as has been reviewed in Ref. [4]. The advantages of HTS are that they can be used up to a high magnetic field of > 16 T and at an elevated temperature operation of > 10 K, both of which are clearly higher than those for Low-Temperature Superconducting (LTS) conductors and magnets. In addition, the higher cryogenic stability is an essential quality, which then assures that a higher current density of a conductor is achievable.

At NIFS, the HTS STARS (Stacked Tapes Assembled in Rigid Structure) conductor concept has been proposed and developed [1–3]. The internal structure of this conductor has a simple stacking of REBCO (Rare-Earth Barium Copper Oxide) tapes imbedded in a copper stabilizer. The outside of the conductor has a stainless-steel jacket for mechanical reinforcement. A 100-kA current was successfully achieved by a prototype conductor sample tested in 2014, with a total 3-m length, having a 300-mm portion under a 5 T magnetic field and a 20 K temperature [1, 5–7]. It is considered that this prototype test had proven the basic feasibility of the concept of the simple stacking of HTS tapes.

Before the realization of the FFHR fusion reactor, construction of a next-generation helical device is expected to extend the plasma experiment of the presently working Large Helical Device (LHD) and to examine the feasibility of advanced reactor components. Whether the HTS magnet can be applied to such a device is now being examined. For this purpose, a relatively smaller conductor is required, and presently, the target is found at 10 - 20 kA current in a magnetic field of ~10 T and at a temperature of ~20 K. Three types of HTS conductors with different internal configurations are being developed. One is the STARS, and the other two options are FAIR [8, 9] and WISE [10], which also use REBCO tapes. For all these conductors, the target is to achieve a maximum magnetic field of > 10 T on the coils at an operation temperature of 20 K. A crucial requirement is to achieve a high current density of 80 A/mm^2. 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. A critical current was observed and compared with

author's e-mail: yanagi@nifs.ac.jp

*) This article is based on the presentation at the 30th International Toki Conference on Plasma and Fusion Research (ITC30).

© 2022 The Japan Society of Plasma Science and Nuclear Fusion Research

expectations. And the development is continuing.

2. 20-kA-Class STARS Conductor

In the present phase of the development of the STARS conductor to be used in the next-generation helical experimental device, a scaled-down conductor with an 18-kA nominal operation current was designed and developed. Figure 1 shows the cross-sectional images of the conductor. Though the prototype 100-kA conductor sample was fabricated with a stainless-steel jacket sustained by bolts, the present conductor employs laser beam welding (LBW) to seal the stainless-steel jacket. An initial testing of LBW confirmed that the maximum temperature during the welding was limited to ~44°C, which was well below the specified value of 200°C for REBCO tapes. For the present conductor, 45 4-mm-wide EuBCO tapes (FESC-SCH04), manufactured by Fujikura Ltd., were used. A 3-m-long straight conductor sample was fabricated as shown in Fig. 2 (a). 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 [1, 2]. This time the internal electrical insulation was omitted as the first trial.

3. Experiment in Liquid Nitrogen

The 3-m-long conductor sample was first tested in liquid nitrogen at a temperature 77 K with no external magnetic field. A typical example of the critical current measurement is shown in Fig. 3 where the observed voltage along the sample is plotted as a function of the sample current. In this case, the critical current was evaluated at 3,950 A. The observed critical current was found to be slightly lower than the expected value by multiplying the critical current of a single tape by the number of tapes, which is understood by the self-field effect of the transport current [5, 6]. The critical current measurements were repeated multiple times by having thermal cycles (warming up the sample and cooling it down again). The trend of the observed critical current is shown in Fig. 4 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 another ~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

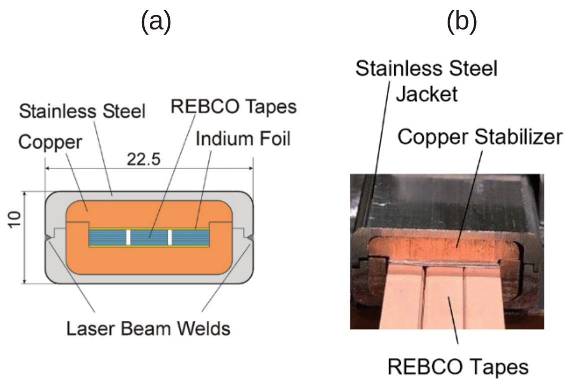

Fig. 1 (a) Schematic cross-sectional image of the STARS conductor sample and (b) a photograph of the STARS conductor sample during fabrication.

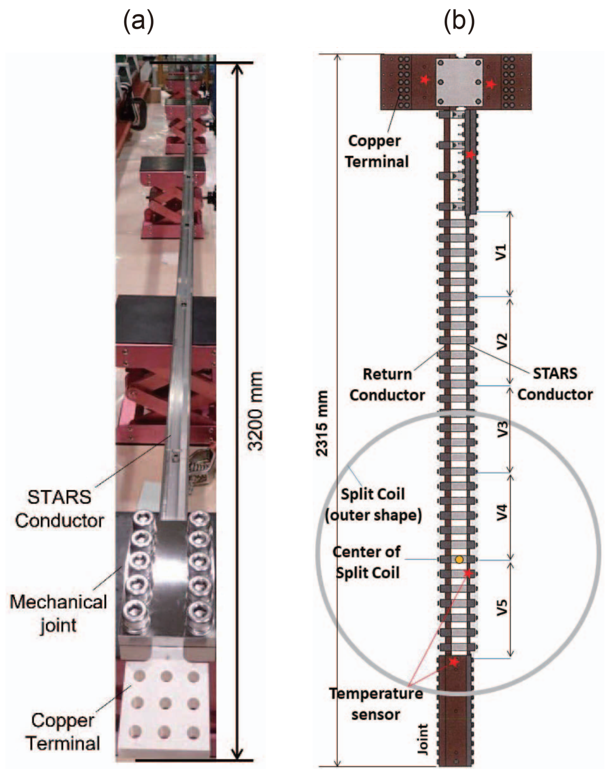

Fig. 2 (a) A STARS conductor sample of a 3-m-length. (b) Schematic image of the sample setup for the cryogenic testing of the STARS conductor (originally shown in (a)) prepared as a 2-m length. A return-conductor is situated by the sample conductor with a joint in between.

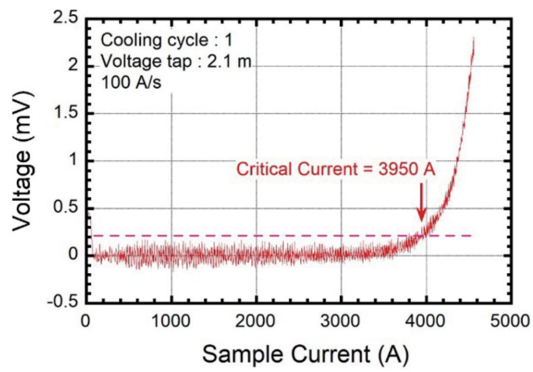

Fig. 3 Measured voltage as a function of the current for the 3-m-long STARS conductor sample tested in liquid nitrogen. A critical current of 3950 A is evaluated in this case by the voltage signal of 0.21 mV (indicated by the dashed line) using the criterion of 1 μV/cm for the critical electrical field.

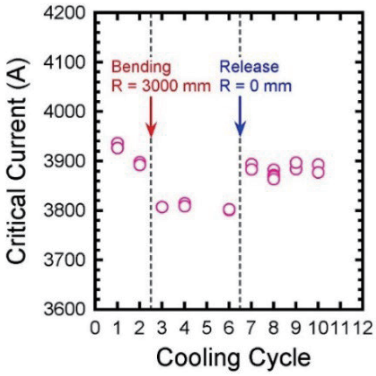

Fig. 4 Measured critical current as a function of the cooling cycle. During the cooling cycles of 3, 4 and 6, a bending strain was exerted with a bending radius (R) of 3,000 mm.

where the surface of the conductor touched the surface of a stainless-steel jig with a 3,000-mm radius. Having released the bending 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. In the next step of this experiment, the conductor will be further bent with a bending radius of < 1,500 mm and reported elsewhere with a precise analysis.

4. Experiment in Cryogenic Helium Gas and Magnetic Field

In the next step, this conductor sample was tested in the large superconductor testing facility at NIFS. The sample was prepared by reconfiguring the former one to have a 2-m length. A return-conductor was situated at the side of the sample conductor, as is shown in Fig. 2 (b). The electrical current was supplied to the conductor sample from current-leads through joints. The two conductors were connected with a joint at the bottom of the sample. For these joints, a mechanical lap joint technique similar to that used in [7] was used. The experiment was carried out at temperatures of 20 K and 40 K. The critical current was observed at 11.2 kA with 40 K, 8 T and at 13 kA with 40 K, 6 T. A 20-kA current was stably transported at 8 T, 20 K, which confirmed that the critical current was higher than this condition. Due to the limitation of the facility in this experiment, the maximum current was limited to 20 kA.

In this experiment, there was a serious mistake that terminated the experiment by damaging the sample conductor. As is shown in Fig. 6, in a 40 K test, there was a rise of a voltage from the section with a voltage tap V5 in Fig. 2 (b) near the joint. However, this voltage signal was not fed into the quench detection system. Instead, only the voltage near the sample center, V3, was monitored, which began to rise after some delay and remained much lower than V5. The rapid rise of the total voltage terminated the current supply. As is shown in Fig. 6, a considerable temperature rise was observed in the joint section. After this event, it was not possible to continue the experiment, and later, the sample was examined to be found locally melted and cut near the joint section.

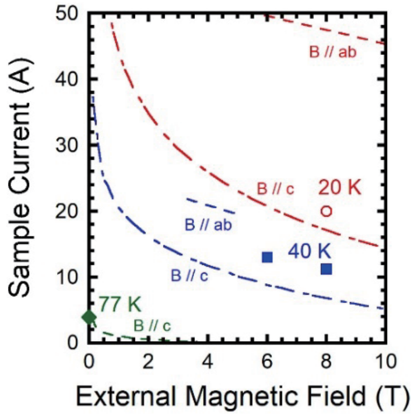

Fig. 5 Achieved sample current as a function of the externally applied magnetic field with temperatures at 77 K (green), 40 K (blue), and 20 K (red). Closed symbols show quench points where critical currents were evaluated, whereas the open symbol (at 20 K, 8 T) was not accompanied by a quench. The dashed and dash-dotted curves represent the expected critical current using its critical current data for single tapes (see explanation in the main text).

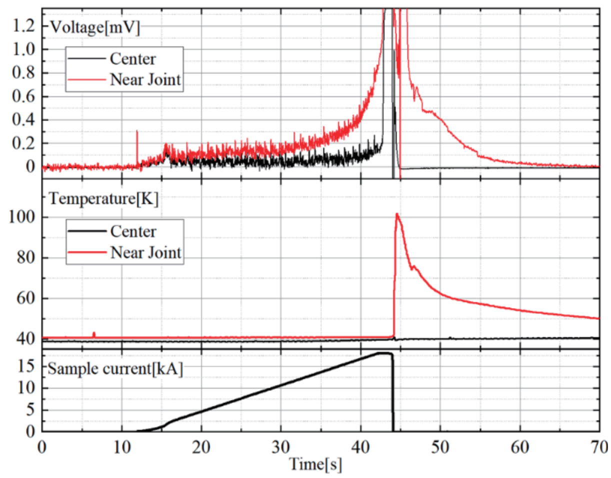

Fig. 6 Temporal waveforms of the voltage (top) and temperature (middle) both at the center of the conductor sample and near the joint, and the sample current (bottom) observed in the conductor test in which there was a failure of quench detection.

5. Discussion

As shown in Fig. 5 by the closed squares, the critical current was observed at 40 K. Above and below the two measured points (at 6 T and 8 T), two curves are indicated. They are the expected critical current values obtained by multiplying the critical current of a single tape by the number of tapes (45) used in the present conductor sample. For the dash-dotted curve, the critical current of a single tape is obtained for the case where the magnetic field is applied perpendicular to the tape surface or in parallel to the *c*-axis of the lattice of the superconducting layer. The dashed curve corresponds to the case where the magnetic field is applied parallel to the tape surface, or parallel to the *ab*-axis of the lattice. It is noted that the presently used EuBCO tape has artificial pinning centers so that the anisotropy of the critical current against the orientation of the magnetic field is alleviated compared to the case with conventional REBCO tapes. However, the critical current still degrades when the magnetic field is applied in parallel to the *c*-axis. In order to precisely analyze and obtain the expected critical current for the whole conductor with a bundle of stacked tapes, the self-field effect by the transport current should be taken into account, as was done in Refs. [5, 6]. Presently, due to the lack of the critical current data of a single tape at 40 K especially around 8 T, it is not possible to make a precise calculation. In addition, for 20 K where there is data for a single tape, the critical current of the conductor was not measured due to the current limitation in the present setup.

Regarding the quench protection, the STARS conductor employs the conventional dump resistor method in the present design to be used in the next-generation helical device. A crude estimation with a zero-dimensional model gives a required discharging time constant, as shown in Fig. 7, as a function of the 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 to < 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) [3]. On the other hand, for a higher current density of 80 A/mm^2, it is found that a discharging time constant of < 3 s is required to limit the hot-spot temperature to be < 200 K. In the experimental result shown in Fig. 6, there was a > 5 s delay before the sample current was terminated, because of a mistake in the quench detection, which was too late. It is understood that the hot-spot temperature rose above the melting point of stainless steel. A more precise analysis of this observation is ongoing with a numerical simulation for the quenching process.

It is noted that the discussion is still continuing regarding the validity of simple stacking of HTS REBCO tapes for large-current conductors. Increase of AC losses and formation of non-uniform current distribution among HTS tapes are the two major concerns with a lack of twisting and transposition. It has been discussed that the AC losses are not significantly increased from the case with twisting and transposition of REBCO tapes [11] and this especially holds for stationary operated magnets for helical devices. The non-uniform current distribution is a serious problem for LTS conductors, which degrades cryogenic stability. In contrast, due to the orders of magnitude of a higher stability margin for the HTS, it may not become a serious problem. This was confirmed in a simple experiment using a five-layered stack of REBCO tapes and non-uniform current feeding [12]. This feature is being examined by numerical simulations which will be presented elsewhere.

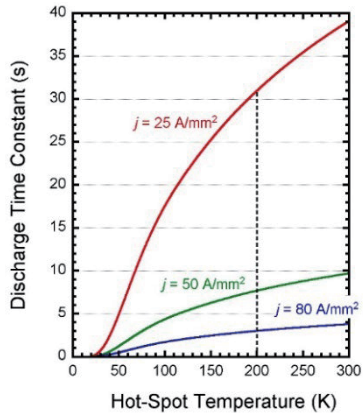

Fig. 7 Required discharging time constant versus the allowable hot-spot temperature evaluated for the STARS conductor with current density j of 25, 50, and 80 A/mm^2.

6. Summary

The STARS HTS conductor is being developed to be used in the next-generation fusion experimental devices with a rated current of 18 kA at 20 K and 10 T. A 3-m conductor sample was fabricated with laser beam welding in the stainless-steel jacket and first tested in liquid nitrogen with no external magnetic field. Then, the same sample was tested in the superconductor testing facility under a magnetic field of < 8 T with temperature control at 20 - 40 K by helium gas cooling. A stable operation at 20 kA current was confirmed. In the next phase, a 6-m conductor sample will be tested and reported elsewhere.

Acknowledgements

The authors thank Hiro Togashi, Yasuyuki Tanaka from Hitachi, Ltd. for fabricating the STARS conductor sample (3-m long) and for reconfiguring it (2-m long) to be tested in the superconductor testing facility.

[1] N. Yanagi *et al.*, Nucl. Fusion **55**, 053021 (2015).
[2] N. Yanagi *et al.*, Cryogenics **80**, 243 (2016).
[3] N. Yanagi *et al.*, J. Fusion Energy **38**, 147 (2019).
[4] P. Bruzzone *et al.*, Nucl. Fusion **58**, 103001 (2018).
[5] Y. Terazaki *et al.*, IEEE Trans. Appl. Supercond. **24**, 4801305 (2014).
[6] Y. Terazaki *et al.*, IEEE Trans. Appl. Supercond. **25**, 4602905 (2015).
[7] S. Ito *et al.*, Fusion Eng. Des. **136**, 239 (2018).
[8] T. Mito *et al.*, J. Phys. Commun. **4**, 035009 (2020).
[9] Y. Onodera *et al.*, J. Phys. Conf. Ser. **1559**, 012118 (2020).
[10] S. Matsunaga *et al.*, IEEE Trans. Appl. Supercond. **30**, 4601405 (2020).
[11] D. Uglietti *et al.*, Cryogenics **110**, 103118 (2020).
[12] T.A.J. Meulenbroeks *et al.*, J. Phys. Conf. Ser. **1293**, 012065 (2019).