Current-carrying capability of the 100 kA-class HTS STARS conductor for the helical fusion reactor FFHR-d1

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Abstract. A 100-kA-class conductor using REBCO high-temperature superconductor (HTS) is proposed as one of the conductor options for the helical coils of the LHD-type helical fusion reactor FFHR-d1. We named it STARS (Stacked Tapes Assembled in Rigid Structure) conductor. Current carrying capability of such a simply-stacked tape conductor is an important issue. We fabricated and tested a 100-kA class STARS prototype conductor sample to verify whether a premature quench occurs. The conductor sample is a one-turn short-circuit coil with a race-track shape having a bridge-type mechanical lap joint. The transport current of the sample was induced by changing the external magnetic field, and the critical current of the sample was measured. A numerical analysis of the critical current is being performed by self-consistently solving the spatial distributions of the current density and magnetic field among the tapes to verify the measured critical current of the samples.

1. Introduction

The conceptual design activities of the LHD-type helical fusion reactor FFHR-d1 are progressing at National Institute for Fusion Science (NIFS). The helical coils of FFHR-d1 have the major radius of 15.6 m and the toroidal magnetic field of 4.7 T [1]. To produce this field, an operating current of 94 kA is required for a conductor of the helical coils at the maximum magnetic field of 11.8 T. We proposed a conductor using the high-temperature superconductor (HTS) as one of the options of the helical coil conductor. This conductor consists of simply-stacked REBCO HTS tapes, a copper stabilizer and a rigid stainless-steel structure. We named it STARS (Stacked Tapes Assembled in Rigid Structure) conductor. The STARS conductor is mechanically rigid because of having no voids due to the fact that there is no twisting nor transposition among tapes. The conductor has high cryogenic stability, and low refrigeration power is supposed to be required with elevated temperature operations at >20 K in comparison to selecting low-temperature superconducting (LTS) conductor options [2, 3]. Furthermore, it is proposed that the large-diameter complex-shape helical coils are constructed by connecting conductor segments [4] (or coil segments [5]), exploiting the advantage of HTS. The conductor without including any twisting and transposition, however, may experience current carrying instability. The purpose of the present study is to examine this feature. On the other hand, it should be noted that the simply-stacked tape configuration does not give any problem to the required accuracy of the magnetic field of the helical fusion reactor, since the inhomogeneity of the
conductor current due to magnetic shielding is practically canceled with a toroidal symmetry along the helical coils [4].

The feasibility studies of the HTS option for FFHR have been progressing since 2005 [6], [7], then in our previous study in 2012-2013 [8]-[10], we fabricated and tested 30-kA-class HTS conductor samples using 20 GdBCO tapes of 10-mm width, and measured the critical currents at 45 kA with the temperature of 20 K and bias magnetic field of 6.1 T and at 69 kA with 4.2 K, 1.2 T. In the series of these experiments, the validity of the conductor fabrication and the experimentation methods have been verified to proceed to a 100-kA-class HTS conductor testing.

In this paper, the fabrication and test of a 100-kA-class HTS STARS conductor sample are reviewed and a numerical analysis of the critical current has been improved from the previous study to verify whether a premature quench occurs in the 100-kA test.

2. Experiment

2.1 100 kA-class HTS conductor sample

Figure 1 shows cross-sections of the 100-kA-class HTS conductor designed for FFHR-d1 and a sample conductor that we fabricated and tested. The REBCO-type GdBCO tapes were employed in this experiment produced by Fujikura Ltd. (FYSC-SC10). The tape has the following layered structure: Hastelloy substrate (100 μm), buffer layers (0.5 μm), GdBCO (2.3 μm), silver (8 μm), tin (2-4 μm) and copper (100 μm). The critical current of this tape having a width of 10 mm was ~650 A at 77 K, self-field. Fifty four tapes (3 rows and 18 layers) were simply stacked in a stabilizing oxygen-free copper (OFC) jacket without any impregnation or soldering. The copper jacket was then installed in a stainless-steel jacket, which was assembled by bolts. As is shown in figure 2, the conductor sample formed a one-turn short circuit coil with a racetrack shape having no current leads. For measuring the current of the sample, Rogowski coils and Hall probes were employed [9]. Voltage taps, temperature sensors and heaters were attached to the stainless-steel jacket as indicated in this figure. The straight sections of the sample were surrounded by glass-fiber reinforced plastic (GFRP) jackets for thermal insulation. One side of the straight sections has a bridge-type mechanical lap joint (the “joint part”) developed in Tohoku University [11], [12]; while the other side has no joint (the “continuous part”). The tapes were overlapped in a step-wise pattern at the joint part and then the copper side (GdBCO side) of the tapes was mechanically connected face-to-face through inserted indium sheets. The details of the joint part and its experimental results are described in [13].

![Image](image_url)

**Figure 1.** Cross-sectional images of (a) the 100-kA class HTS STARS conductor designed for the helical coils of FFHR-d1 fusion reactor and (b) the prototype conductor sample fabricated in this experiment.
2.2 Experimental Setup

The sample was immersed in liquid helium in the cryostat of the large-scale superconductor testing facility at NIFS. The current was induced in the sample by changing the background magnetic field, which was generated by a 9-T split coil with a 1-m diameter. The sample temperature was controlled by heaters attached on the stainless-steel jackets.

2.3 Experimental Result

Figure 3 shows one of the measurement results of the critical current of the 100-kA HTS conductor sample. The continuous part of the sample was heated up to 45 K (by the sensor reading) using heaters. The current was induced in the sample by changing the bias magnetic field from 3.9 to 2.4 T. The sample quenched after reaching the maximum current of 73 kA. We note that the sample current was evaluated by the Rogowski coils in the present analysis since it was confirmed that the Hall probe signals contained the magnetic field generated by the shielding currents induced in the HTS tapes, whereas the Rogowski coils did not count this. For precisely evaluating the sample current, calibration tests of the Rogowski coils were performed at room temperature [9] and in liquid nitrogen. We also note that the difference between the currents measured by two Rogowski coils was within 1%; hence, only the current measured by one of the Rogowski coils is shown in figure 3.

The voltage waveform of the continuous part of the sample is shown in figure 4 as a function of the sample current. The waveform is obtained by removing the inductive component from the raw data of the voltage. The inductive voltage is estimated by the temporal derivation of the bias magnetic field multiplied by a proper coefficient. The dashed line in the figure is obtained by a regression analysis using the following equation:

\[ V = V_C \left( \frac{I_S}{I_C} \right)^n , \]  

where \( V \) and \( V_C \) are the measured voltage at the continuous part and the voltage criterion of 20 μV corresponding to the electric field criterion of 1 μV/cm (here the voltage tap length is 20 cm), respectively. The parameters \( I_S \), \( I_C \) and \( n \) are the sample current, the critical current of the sample determined by the criterion of 1 μV/cm and the n-value (resistive transition index), respectively. The critical current of the sample was evaluated to be 72.6 kA in this case. We also observed a critical current of 67.4 kA at 45 K, 4.3 T. We note that the sample temperature of 45 K shown here is the temperature read by Cernox temperature sensors attached on the stainless-steel jackets. In this

Figure 2. (a) Photograph and (b) Schematic view of the overall conductor sample. Locations of voltage taps, temperature sensors, heaters and thermal insulations are indicated in (b).
experiment, one of the two heaters attached at the sides of the stainless steel was lost and hence the actual temperature of the HTS tapes might have been lower than this value. The detail of the temperature analysis is described below.

Figure 3. Waveforms of the sample current and the bias magnetic field at 45 K.  

Figure 4. Voltage waveform of the continuous part of the 100-kA conductor sample as a function of the sample current.

3. Numerical analysis of the critical current

The critical current of the sample conductor was examined by the following numerical analysis to evaluate the critical current of the sample. In this analysis, the critical current of the conductor sample was calculated using the critical current density of a single HTS tape dependent on the local magnetic field, its orientation and temperature. In our first analysis [9], we considered only the local self-field perpendicular to the wide face of the tape. The calculated critical currents were in fairly good agreement with the experimentally observed values. After that, we performed the analysis considering the local magnetic field, its orientation and the bias magnetic field [14]. As a result, the critical current was calculated at various temperature and magnetic field.

3.1 Calculation model

In this experiment, it is considered that a non-uniform current distribution in the conductor sample is formed due to imbalance of the impedance among HTS tapes. The sample current, however, reached the critical current without having a premature quench. We may then consider that the inhomogeneous currents among tapes are stably redistributed when the whole conductor current approaches the critical current, owing to the high cryogenic stability of the HTS tapes. Figure 5 shows the calculation region of this analysis. The calculated cross-section was determined as a cross-section at the highest external magnetic field. The bundle of GdBCO tapes is regarded as a one-body conductor, which is divided into 405 elements. The origin of the coordinate is given at the center of the sample. At first each element is given an initial current, and the self-field of the sample at each element is calculated by the Biot-Savart's law taking into account the whole sample geometry (the calculation point of the field is at the center of each element). Then, the critical current of each element is evaluated by the magnetic field intensity (= self-field + bias field), its orientation and the sample temperature using the critical current characteristics of a single tape given by the model proposed by F. Grilli et al. [15]. If the current of any element exceeds the critical current of that element, the current is reduced to the critical current and the residual current is equally distributed to other elements as long as each of these current is lower than the critical current. This process is iterated, by developing non-uniform current distribution, until the current of every element reaches the critical current. Then, the critical current of the conductor sample is defined as the summation of the currents in all the elements.
3.2 Critical current characteristics of HTS

In the previous study [14], the critical current characteristics were evaluated by percolation model [16]. The necessary parameters of the percolation model referenced from the literature were parameters obtained another GdBCO tape instead of the actual GdBCO tape used in this experiment. In this case, the critical current characteristics of the GdBCO tape were evaluated by the model proposed by F. Grilli et al [15] for precise analysis. The model is an useful method to describe the critical current density and the magnetic field characteristics of HTS tapes with few scaling parameters. Parameters are obtained from the actual GdBCO tape provided by the tape supplier. The characteristics are formulated by the following equations:

$$J_C(B_{\parallel}, B_{\perp}) = \frac{J_{C0}}{\left(1 + \sqrt{(kB_{\parallel})^2 + B_{\perp}^2 / B_C}\right)^b}$$

(2)

where $J_{C0}$, $B_C$, $b$ and $k$ are numerical parameters.

3.3 Validations of experimental results by numerical analysis for 30 kA-class HTS conductor sample

The validation of the above mentioned model was performed for the experimental results for a 30 kA class HTS conductor sample having 20 GdBCO tapes (2-rows and 10-layers). The details of the 30-kA sample were described in [9]. Figure 6 shows the critical currents of the 30-kA sample obtained by the experiment and numerical analysis as a function of the bias magnetic field at each temperature. Symbols and curves in the figure show the results of the experiment and the analysis, respectively. The experimental and the analytical results are in fairly good agreement at the lower field region, whereas there is still a discrepancy between the results at the higher field region. This may be due to the
difference of the critical current characteristics of the GdBCO tape used in the experiment and the analysis.

3.4 Calculation results for the 100 kA-class HTS conductor sample

The critical current analysis for the 100-kA sample was performed. Figure 7 shows the critical currents of the 100-kA sample obtained by the experiment and numerical analysis as a function of the bias magnetic field. In this case, the experimental results at the temperature reading of 45 K are located between the calculated results of 30 K and 40 K. As stated above, the tape temperature is considered to be lower than the temperature indicated by the sensors attached on the stainless-steel jacket. So, a numerical analysis to evaluate the actual temperature of tapes was performed. Figure 8 shows schematic illustrations of a calculated region in the sample. The finite element method was used in this analysis using ANSYS™. The boundary conditions are also shown in figure 8. Physical properties were quoted by CryoComp, which provides the physical property data of various materials. A physical property of a HTS tape was determined by the mixture rule of copper and stainless-steel. The calculated results are shown in figure 9. A red zone in the figure corresponds to the position of the heater. The average temperature in the tape from the center of the straight part within 100 mm is about 38 K. This seems to support the result of the critical current analysis of the 100-kA conductor sample. Thus, it is confirmed that the 100-kA sample did not show a premature quench.

![Figure 6](image1.png)

**Figure 6.** Critical currents of the 30-kA-class conductor sample obtained by the experiment and numerical analysis as a function of the bias magnetic field at each temperature. Symbols and curves show the results of the experiment and analysis, respectively.

![Figure 7](image2.png)

**Figure 7.** Critical currents of the 100-kA-class conductor sample obtained by the experiment and numerical analysis as a function of the bias magnetic field. Symbols and curves show the results of the experiment and analysis, respectively.
Figure 8. Schematic illustration of a calculated region of the temperature analysis. The boundary conditions were also shown in the figure.

Figure 9. Temperature distribution in the conductor analyzed by ANSYS.

4. Summary

A 100 kA-class HTS STARS conductor sample as a prototype conductor for the helical fusion reactor FFHR-d1 was fabricated by simply stacking GdBCO tapes. The current was induced in the short-circuit sample by changing the bias magnetic field. The critical current of 67.4 kA and 72.6 kA were measured at the bias magnetic field of 4.3 T and 2.8 T, respectively, at the temperature of ~38 K.

A numerical analysis of the critical current of the sample was performed by solving self-consistently the spatial distribution of the magnetic field and current density in the sample. The calculated values for the 30-kA sample agrees well with the experimentally obtained values at the lower field region, whereas there is still some discrepancy at the higher field region. This may be caused by the difference of the critical current characteristics of the tape used in the experiments and the analysis. As a result of the analysis for the 100-kA sample, it is confirmed that the sample did not show a premature quench. Thus, we consider that the STARS conductor is applicable for large-current DC-operating conductors such as for the helical coils of FFHR-d1.

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