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K. Takahashi, A. Badel, A. Zampa, T. Okada, S. Awaji, et al.. Performance Test of 20-Stacked Two-Tapes-Bundled REBCO Pancake Coils for Upgrading of 25-T Cryogen-Free Superconducting Magnet to 30 T. IEEE Transactions on Applied Superconductivity, 2023, 33 (5), pp.4601405. 10.1109/TASC.2023.3252496 . hal-04311884

HAL Id: hal-04311884

<https://hal.science/hal-04311884>

Submitted on 28 Nov 2023

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Performance Test of 20-Stacked Two-Tapes-Bundled REBCO Pancake Coils for Upgrading of 25-T Cryogen-Free Superconducting Magnet to 30 T

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Abstract—For next generation of high field cryogen-free superconducting user magnets, we adopt a robust coil concept, which consists of two tapes co-wound in a face-to-back configuration, a fluorine-coated polyimide tape as the inter-bundle insulation and thin FRP plates glued on the coil edges. To validate our coil design, we investigated electromagnetic and current-voltage properties of 20-stacked REBCO pancake coils wound with Fujikura EuBCO tapes with the robust coil concept at 4.2 K under a background field of 14 T. The inner and outer diameters and total height of the coils are 68 mm, 266 mm, and 101 mm, respectively. The average of measured hoop and axial strain on the outermost winding at the mid plane of the 20-stacked coils were 0.23% and -0.15% respectively at a hoop stress of 370 MPa estimated by the *BJR* relation. The *I-V* properties of the coils showed no anomalous behavior up to 25 T totally generated by the coils and background field, suggesting that our coil structure has an advantage against large electromagnetic stress.

Index Terms—Axial strain, electromagnetic stress, high field superconducting magnet, hoop strain, REBCO coil.

I. INTRODUCTION

A 25 T CRYOGEN-FREE superconducting magnet (25T-CSM) developed at the High Field Laboratory for Superconducting Materials (HFLSM), Institute for Materials Research, Tohoku University [1] has been successfully operated more than six years; it has been subjected to various kinds of experiments as a user magnet. The 25T-CSM consists of CuNb/Nb₃Sn and NbTi outsert coils and Bi₂Sr₂Ca₂Cu₃O_y (Bi2223) insert pancake coils. Now, an upgrade plan to a 30T CSM by replacing the Bi2223 insert coils with REBa₂Cu₃O_y (REBCO, RE: rare earth and yttrium) coil was underway [2], since REBCO tapes have high in-field critical current density

This work was supported by JSPS KAKENHI under Grant 18H05248. (Corresponding author: K. Takahashi.)

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as well as great mechanical properties [3], [4]. Meanwhile, a new 33T-CSM project was launched at the HFLSM in 2022 [5]. The 33T-CSM will consist of newly-designed 14 T outsert coils wound from both CuNb/Nb₃Sn and NbTi Rutherford cables, and a 19 T REBCO insert coil. In any case, REBCO coil technology plays an important role in the success of the magnet development projects.

Coil technologies using REBCO tapes can be broadly classified into two types: layer-winding and pancake-winding methods. In layer-wound REBCO coils, insert coils for GHz-class NMR magnets have been developed and put into practical use [6], [7]. As for pancake coils, NHMFL reached 32 T with an all-superconducting magnet in 2017 [8], and IEECAS successfully generated 32.35 T as well in 2019 [9]. In terms of winding technology of REBCO pancake coil, no-insulation technique has attracted much attention from the viewpoint of quench protection. Since Hahn et al. demonstrated the NI coils [10], a partial-insulation coil [11], a metal-as-insulation coil [12] and a pancake coil using an electrically conductive epoxy resin [13] have been proposed. On the other hand, our group has suggested a robust coil concept, in which two REBCO tapes are co-wound and fluorine-coated polyimide tape is used as an inter-bundle insulation as described later. To date, we have investigated mechanical properties of the robust coils with sub-scale double pancake REBCO coils and full-scale four-stacked REBCO coils and have shown the structure has an advantage with respect to the electromagnetic stress [14], [15]. Furthermore, two-tape bundled coil have been shown to be robust against a local degradation in the tape and thermal runaway [16], [17]. In this study, to further validate our coil design for the 30T-CSM, we investigate electromagnetic and current-voltage properties of 20 stacked REBCO pancake coils with the robust coil concept under large electromagnetic stress. The 20-stacked coils were designed and fabricated with the expectation that they will actually be installed into the 25T-CSM by adding required number of coils for generating the target magnetic field after this test.

TABLE I
SPECIFICATIONS OF REBCO TAPE

Superconductor	Eu123 w/ BHO
Tape width (mm)	4.1
Tape thickness (mm)	0.15
Hastelloy thickness (μm)	50
Stabilizer	40 μm plated Cu
I_c @77 K, self-field (A)	223–229
n -value @77 K	≥ 22

TABLE II
SPECIFICATIONS OF 20-STACKED COILS

No. of bundled tapes	2
Tape stacking configuration	face-to-back
Inter-bundle insulation	fluorine-coated polyimide tape
Inner diameter (mm)	68
Outer diameter (mm)	266
Total height (mm)	101
No. of turns / pancake	271–294
I_c of pancake @77 K, self-field (A)	121–174
n -value of pancake @77 K	22–27

II. EXPERIMENTAL

The 20-stacked coils consist of 10 double pancake (DP) coils which are stacks of single pancake (SP) coils electrically connected at their inner copper electrode with a silver plate. Adjacent DP coils are connected at the outermost winding as described later. Each SP coil was wound by the PLD processed EuBCO tape with artificial pinning centers (Fujikura FESCCH04 (40)) [18],[19]. The specifications of the EuBCO tape are listed in Table I. In all the coils, two EuBCO tapes are co-wound in a face-to-back configuration with the superconductor (SC) layer inside and at the start of winding, the SC layer side of both the inner tape and the outer tape (with the end shifted) are soldered to the inner electrode. The coils were wound with a winding tension of 5.5 kgf (90 MPa) for each EuBCO tape. A fluorine-coated polyimide tape is used as the inter-bundle insulation. Thin FRP plates were glued onto the edges of each coil with epoxy resin, which is one of the features of our robust coil concept. Aluminum sheets, divided radially into 12 sections, are sandwiched in each DP coils for conduction cooling as in the case of the four-stacked coils [15]. For all SP coils, the critical current, I_c and n -value were evaluated in liquid nitrogen and were 121–174 A and 22–27, respectively. The coil specifications are listed in Table II. The SP coils are arranged so that its I_c is higher toward the top and bottom edges than at the mid plane, considering magnetic field angle dependence of I_c of the EuBCO tape.

To measure hoop and axial strains, two sets of strain gauges were attached to the outer surface of the winding of SP#10 that is 10th coil from the top as shown in Fig. 1. One set consists of two strain gauges (one for hoop strain, SG160h and the other for axial strain, SG160a) attached orthogonally, with another set on the opposite side circumferentially (SG340h and SG340a). The numbers of 160 and 340 represent the azimuth angle of the coil viewed from top as the direction of the electrodes is 90° .

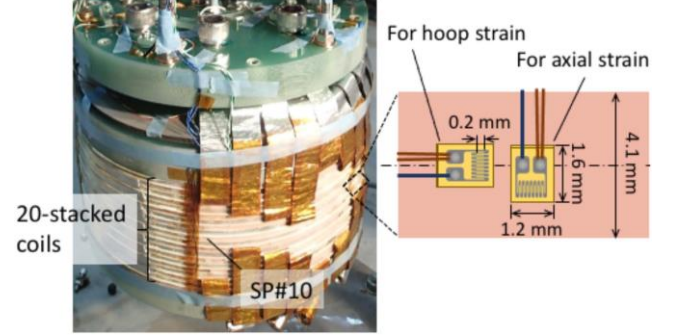


Fig. 1. Photograph of 20-stacked coils and schematic illustration of strain gauge arrangement. Strain gauges of hoop strain (SG160h and SG340h) are attached to the center of the tape width, and for axial strain (SG160a and SG340a) are slightly offset to the lower side. Active length of the gauge is 0.2 mm.

A data logger UCAM-60B (Kyowa Electronic Instruments Co., Ltd.) was used for the strain measurements.

Hoop stress tests of the coils were performed using a 14 T large bore superconducting magnet at National Institute for Materials Science. The coils were immersed in liquid helium bath and an operating current was supplied by a DC current source (up to 300 A) under a background field of 14 T.

III. RESULTS AND DISCUSSION

The operating current-voltage (I - V) properties of the coils are shown in Fig. 2. Fig. 2(a) shows the I - V properties of SP and DP coils, and Fig. 2(b) shows the voltage across the overall coils. Coils are numbered from the top, with DP#1 consisting of SP#1 and SP#2, DP#2 of SP#3 and SP#4, etc. A balance voltage, which is the voltage difference between the upper and lower 10 SP coils, is also monitored as shown in Fig. 2(c). An inductive voltage of approximately 0.025 V for each SP coil and 0.05 V for each DP coil are observed at a ramping rate of 0.18 A/s, respectively in Fig. 2(a). The 20-stacked coils have totally nine outer electrical joints between adjacent DP coils. At the joint, an additional EuBCO tape with the SC layer outside is soldered to the SC layer side of the inner tape and the outer tape which is longer than the inner one. The SC layer of both tapes in the bundle are soldered to the SC layer of the additional tape in a face-to-face configuration. Then, a silver plate (96 mm long, 8 mm wide, and 1 mm thick) is soldered to make a current path with covering the SC outside sections of the upper and lower DP coils. The resistance of each joint was measured in liquid nitrogen and ranged from 0.09 to 0.25 $\mu\Omega$. There was a concern

about damage due to electromagnetic forces on the joint and the resulting increased resistance. Fig. 2(b) shows that no dissipative voltage appeared without the joint resistance, which was totally less than a few $\mu\Omega$ from inner joints as well as outer ones. No resistive or anomalous voltages, although relatively noisy, were observed also in the balance voltage. The spike noises appearing in the coil voltages are probably due to slight wire movement in the coil. Those reduced drastically in ramping down from 300 A. No noises were observed in measurements up to 300 A at zero background field. These I - V properties indicate that there

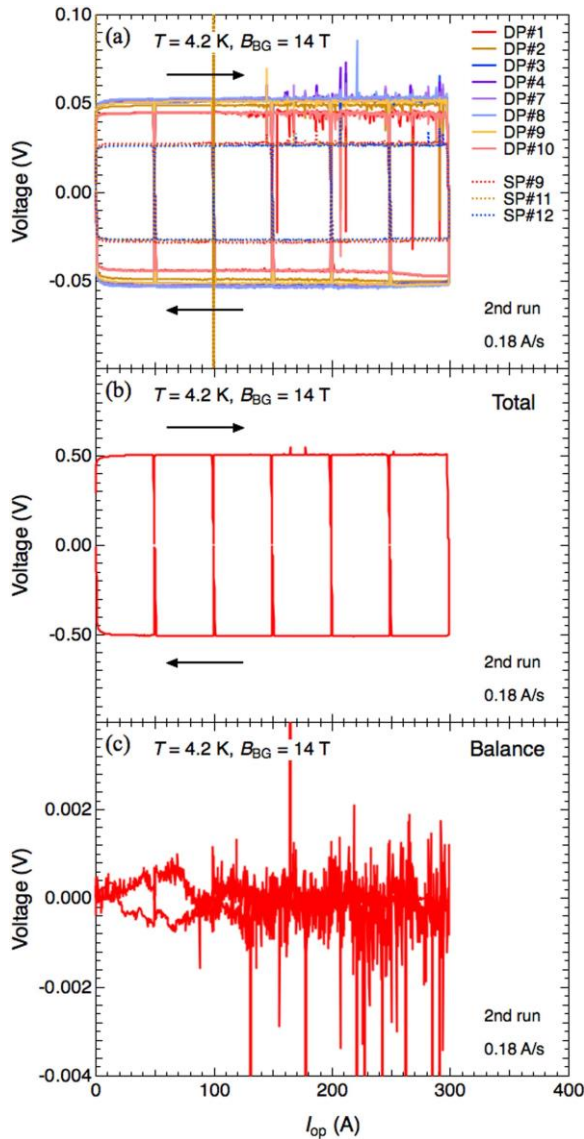


Fig. 2. I - V properties of (a) SP and DP coils in 20-stacked coils, and of (b) the overall coils. Coils are numbered from top to bottom. (c) Balance voltage of the 20-stacked coils as a function of the operating current.

is no serious problem in the windings and connections of the coils.

The magnetic field measured by a Hall probe at the center of the coils is plotted against the operating current in Fig. 3(a). The magnetic field error, which is a difference between the measured data and the fit line is shown in Fig. 3(b). A clear hysteresis for the operating current is observed, which is well-known behavior

as an effect of the screening current in superconducting tapes [20]. In addition to the overall hysteresis, relaxations of the magnetic field as indicated by vertical arrows are observed every 50 A where a plateau of the operating current was made. This behavior is due to the effect of coupling current flowing between the two bundled tapes [21], [22]. The axial magnetic field generated by the coupling current is in the same direction of the magnetic field of the coils. Therefore, when the current sweep is stopped, the coupling current decays with relatively small time constant, and the total axial field decreases during ramping up and increases during ramping down the operating current.

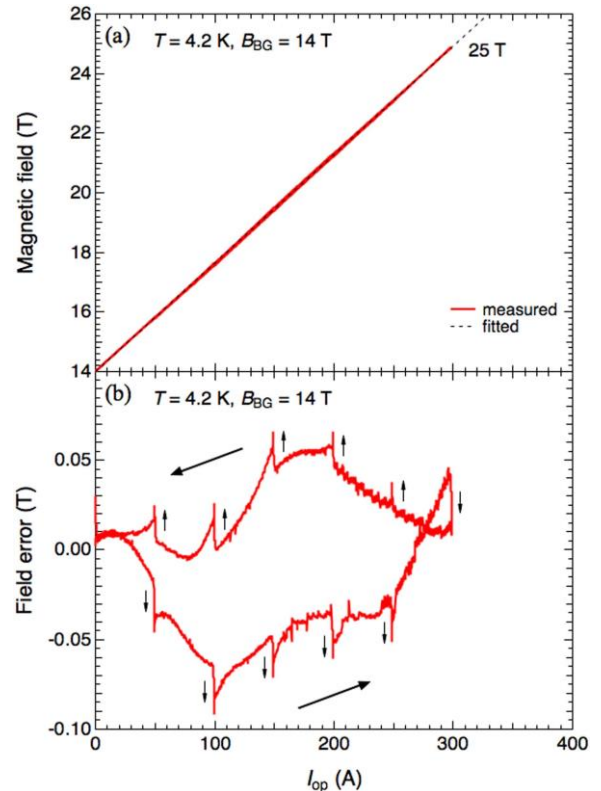


Fig. 3. (a) Generated magnetic field measured by a Hall probe at the center of 20-stacked coils under a background field of 14 T. (b) Difference between the measured value and the fitted line as a function of the operating current.

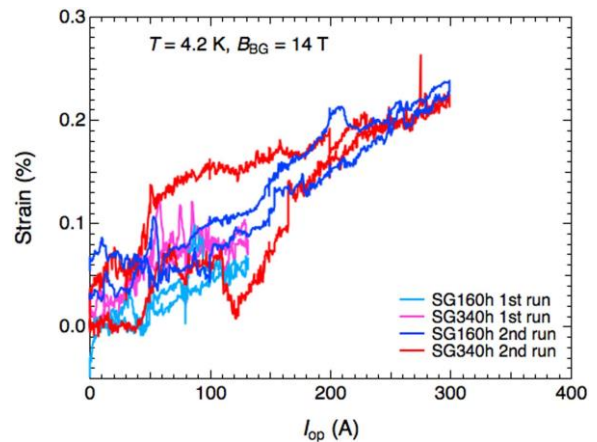


Fig. 4. Hoop strains of SP#10 measured by strain gauges as a function of the operating current

Fig. 4 shows hoop strains obtained from strain gauges on the SP#10. Although the data is noisy, the strains show almost the same trend, and approximately 0.23% at 298 A. The stress/strain distribution in the coil calculated by the BJR relation and FEM analysis are shown in Fig. 5, where B , J and R are a magnetic flux density, current density and coil radius, respectively. The measured hoop strain is in good agreement with the FEM analysis taking into account the thin FRP plates glued on the edges of the coil [23].

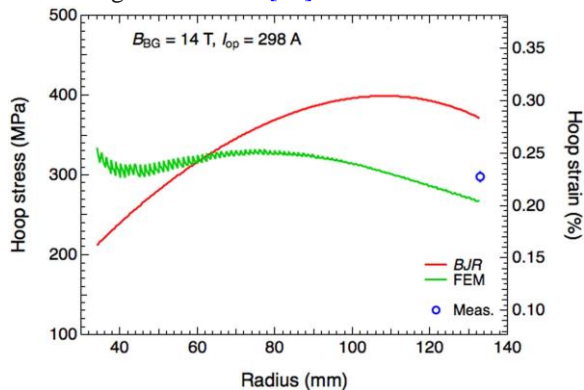


Fig. 5. Stress distribution in SP#10 at an operating current 298 A, calculated by the BJR relation and the FEM analysis considering the robust coil concept. Open circle with an error bar represents averaged measured strain.

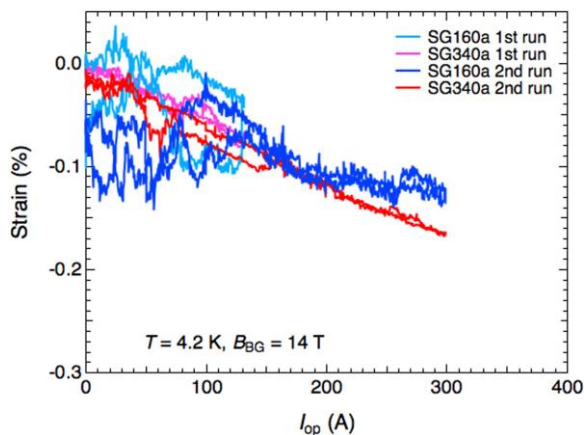


Fig. 6. Axial strains of SP#10 measured by strain gauges as a function of the operating current.

According to the FEM calculation, the maximum hoop stress is approximately 330 MPa, which is smaller than that estimated by the BJR relation. This result is consistent with those we have reported previously [14], [15], suggesting one of the advantages of the robust concept.

Fig. 6 shows axial strains measured on the SP#10 coil in the axial midplane of the 20-stacked coils. The axial strain at 298 A, averaged over the two gauges, is approximately -0.15% , being compressive strain. Assuming simple compressive deformation, i.e. the coil is compressed uniformly, the axial stress is estimated to be 195 MPa from the strain with a Young's modulus of 130 GPa for the EuBCO tape. This stress value is larger than the compressive stress

estimated in a comparable-sized magnet. This discrepancy in stress estimations indicates that the axial deformation is not simple, especially at the outermost winding of the coil, where bending of the tape may be also taken into account for the strain analysis.

IV. CONCLUSION

We investigated the electromagnetic and current-voltage properties of 20-stacked REBCO pancake coils with the robust coil concept under a background field of 14 T. The coil could be operated with no degradation under an electromagnetic stress up to 330 MPa estimated by the FEM analysis considering the robust coil concept. The obtained strain at the outer surface of the coil (SP#10) at the midplane of the 20-stacked coils, is approximately 0.23%, which is in good agreement to the FEM analysis. It suggests that the coil structure with the robust concept can reduce the maximum stress due to the optimization of stress distribution in the coil. Although the operating current was limited up to 300 A in this case due to the power supply, total magnetic field of 25 T could be generated, and higher magnetic fields are expected to be generated because no serious problems were observed in the current-voltage behavior. This is a benefit of the robust coil concept, and we plan to perform further experiments with this coil, including under a conduction cooling condition.

ACKNOWLEDGMENT

The authors would like to thank Dr. S. Nimori of Cryogenic Station, National Institute for Materials Science and K. Fushimi of High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University for their technical assistance with the experiments.

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