Progress in High-Temperature Superconducting WISE Conductors for Helical Fusion Reactors

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Applying high-temperature superconducting (HTS) conductors to the magnets of Helical fusion reactors, which require a higher degree of three-dimensionality compared to the magnets of tokamak devices, can enhance plasma performance by increasing fusion power. By stacking Rare-Earth Barium Copper Oxide (REBCO) tapes, winding them into specific shapes, and then impregnating them with low-melting-point metals, the strain on the tapes can be minimized. Using this method, a 2-m-long U-shaped WISE (Wound and Impregnated Stacked Elastic tapes) conductor was subjected to current testing at temperatures ranging from 6 to 20 K and magnetic fields of 8 T. The conductor had the capability of maintaining 40 kA for 8 s at 6 K, 8 T with an average engineering current density of 31 A/mm^2, without a temperature rise or quench. Repeated tests at 20 K and 8 T with a maximum current of 22 kA showed no temperature increase, confirming the conductor's mechanical robustness. In the preliminary stages of the energization test, an increase in voltage reminiscent of a quench was observed, even though the current was lower than the critical current value. However, this voltage was suppressed as the maximum value decreased with each repetition of energization. Such behavior is considered similar to a training effect and indicates the movement of REBCO tape inside the conductor.

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1. Introduction

To realize magnetic-confinement nuclear fusion reactors, the strength of the magnetic field is a crucial element and needs to be sufficiently high for effective plasma confinement. This can be achieved using magnets fabricated from high-temperature superconducting (HTS) conductors [1] which offer significant advantages over low-temperature superconductors (LTS) because of their higher critical temperature (T_c) and magnetic field (B_c).

Helical fusion reactors need only an external magnetic field to confine the plasma, thereby eliminating the need for a plasma current for the poloidal magnetic field. Unlike tokamaks, helical plasmas avoid significant magnetic field changes, reducing AC losses and allowing stacked conductors. Tokamaks face large magnetic field changes due to plasma current loss, generating induced electromotive force (EMF) and requiring complex designs of conductor. Helical plasmas, not needing plasma current, avoid these issues and use simpler conductors.

The plasma energy confinement time of helical fusion reactors, which is a critical parameter in fusion research, is proportional to $B_m^{0.8}$ according to a scaling law of helical plasmas [2]. Here, B_m is the magnetic field produced by the magnet. Since increasing the magnetic field strength directly enhances plasma performance, HTS are promising candidates for improving reactor efficiency. However, the complex three-dimensional magnet configuration of helical fusion reactors imposes unique mechanical and electrical constraints on conductor design, necessitating the development of robust and flexible HTS conductors. To address these challenges, this study focuses on evaluating the current-carrying properties of the WISE conductor under low temperatures and high magnetic fields, as a potential solution for helical fusion reactor applications. Additionally, this study provides a detailed evaluation of the training effect and voltage stabilization behavior of the WISE conductor. Previous studies on REBCO tape-based conductors have reported variations in critical current under repeated energization, highlighting the importance of quantitatively assessing these effects. In this study, we analyzed the voltage response of the WISE conductor during repeated energization and demonstrated its potential to improve current distribution uniformity and mechanical stability. Specifically, the post-shaping impregnation and

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reinforcement with armor blocks were found to enhance the mechanical strength of REBCO tapes, contributing to voltage stabilization. These findings offer a new perspective on the design guidelines for high-current-capacity conductors in helical fusion reactors.

The National Institute for Fusion Science (NIFS) has explored three types of HTS conductors with distinctive designs: STARS (Stacked Tapes Assembled in Rigid Structure) [3], FAIR (Friction stir welding, Al-alloy, Indirect-cooling, REBCO (Rare-Earth Barium Copper Oxide)) [4], and WISE (Wound and Impregnated Stacked Elastic tapes) [5]. For FFHR-b3 [6], the expected operating conditions are 20 K and 19 T, necessitating a conductor capable of carrying high currents while maintaining superconductivity. The reactor has a major radius of R_c = 7.8 m and a toroidal magnetic field of B_c = 6.6 T. To achieve this magnetic field strength, a current of 52.1 kA must flow through two pairs of 570-turn helical coils. Given an assumed conductor cross-sectional area of 25 mm × 26 mm, the expected engineering current density is 80 A/mm^2. The WISE conductor was designed with a current limit of 40 kA, which corresponds to an engineering current density of 31 A/mm^2. This limitation arises due to the constraints of the current lead capacity in our testing facility. While the 40 kA (31 A/mm^2) current limit is lower than the expected operational requirement for FFHR-b3, testing under these conditions is essential to assess the mechanical stability and electrical performance of the WISE conductor before scaling up to higher current densities. Evaluating its behavior under high electromagnetic forces and repeated energization cycles provides critical insights into its feasibility for future applications in helical fusion reactors. These conditions simulate the environment that superconducting coils in a helical fusion reactor encounter. The design of the WISE conductor incorporates several key elements to ensure high current density, mechanical stability, and efficient current distribution. First, REBCO tapes are stacked to achieve a high current density while maintaining flexibility. Additionally, the conductor is impregnated with low-melting-point metals, which helps minimize strain and enhance mechanical stability. Furthermore, copper tapes are used to improve current distribution and prevent burning in the feeder section, ensuring reliable performance under high-current conditions.

In previous tests [7], the WISE conductor with 30 stacked REBCO tapes reached ~ 10 kA at T = 40 K and B = 5 T. However, the current feeder section burned out [8], preventing the expected maximum current. This development is crucial for high-current superconducting applications. After improving the current feeder with a stepped connection and more REBCO tapes, we achieved 40 kA, a significant advancement.

2. Overview of the Test Apparatus

Figure 1 shows a schematic of the WISE conductor. This linear conductor, composed of 60 stacked REBCO tapes (Fujikura FESC-SCH12, consisting of a Hastelloy substrate with a thickness of 50 µm, copper stabilization layers on both sides with a thickness of 20 µm each, resulting in a total thickness of about 100 µm, and a width of 12 mm; critical current I_c = 500 A @77 K, s.f.), was designed to be bent into a U-shape and impregnated with U-alloy, which is an alloy of indium (In), bismuth (Bi), and tin (Sn) with a melting point

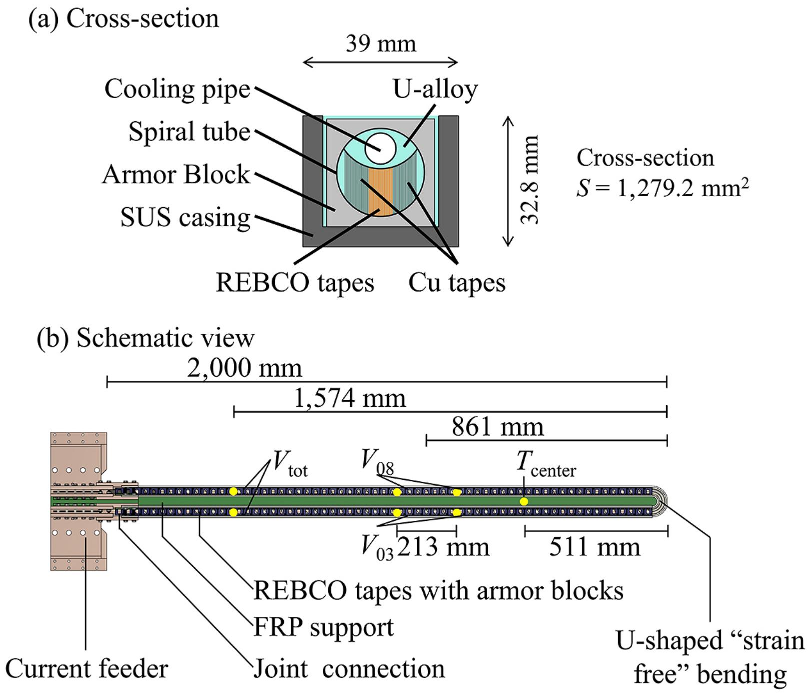


Fig. 1. Schematic of WISE Conductor. (a) Cross-section of WISE. REBCO tapes are sandwiched between stacked copper tapes. Other components include the cooling pipe, spiral tube, armor block, SUS casing, and U-alloy. (b) Voltage taps (V_{tot}, V_{03}, V_{08}) and temperature sensor (T_{center}) at center of magnetic field are shown.

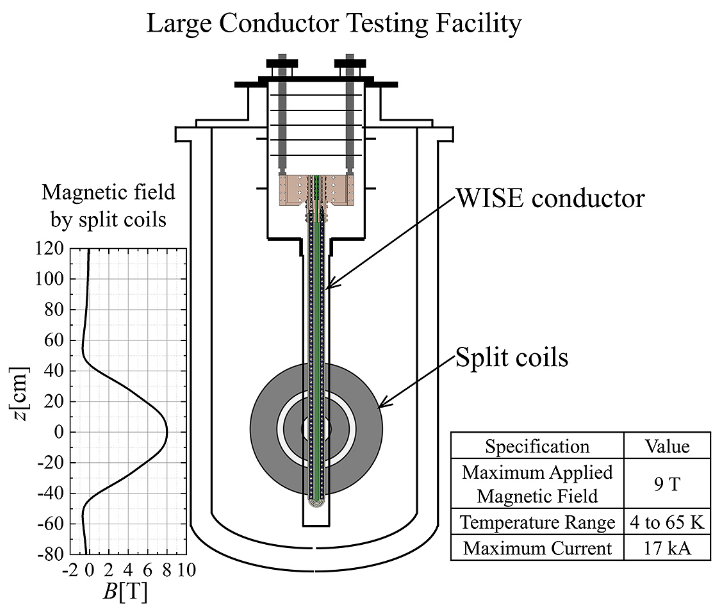
of 60°C. Furthermore, this conductor addresses the issue of burning in the current feeder section, which was a problem observed in conductors previously fabricated and tested using similar concepts [8]. In previous designs, the terminal embedded REBCO tapes in a straight groove and impregnated them with U-alloy. While this simplified fabrication, it led to local current concentration, causing overcurrent beyond the critical current and resulting in burning. To prevent this issue, the present terminal design adopts a stepped groove structure, ensuring uniform current inflow to the stacked REBCO tapes and preventing local overcurrent. Although copper tapes are not directly responsible for preventing burnout, they contribute to the mechanical stability of the conductor by reinforcing the structure around the stacked REBCO tapes. They also enhance thermal stability by facilitating heat dissipation, which is particularly important under high-current conditions. The REBCO tape, which is layered with copper tape, is inserted into a spiral tube (SUS304) along with cooling tubes (SUS304) and protected by armor blocks (titanium), as shown in Fig. 1(a). The copper tapes used here are 12 mm in width and 0.1 mm in thickness. A total of 92 copper tapes were stacked, with 46 tapes on each side of the stacked REBCO tapes. Notably, the conductor, which is approximately 4 m in length, can be flexibly bent at this stage. Subsequently, it was formed into a U-shaped structure, held by a Fiber Reinforced Plastics (FRP) support, connected to the current feeder, and then impregnated with a low-melting-point metal. Voltage taps were installed at key locations for measuring the voltage across the entire superconducting section. The resulting "folded" WISE conductor has a span of approximately 2 m, as shown in Fig. 1(b). The width of the FRP support is 33.2 mm. The diameter of the stacked REBCO tapes in the U-shaped section is 70.2 mm. The WISE conductor was installed in a large conductor testing facility at NIFS, as shown in Fig. 2. This facility has a liquid helium cryostat, and helium gas is utilized to control the temperature of the WISE conductor [9]. The split coils, made of LTS (Nb_3Sn for the inner layer and NbTi for the outer layer), which apply the magnetic field, are cooled by liquid helium [10]. The current tests were conducted under conditions of a magnetic field (B = 8 T) and temperature conditions (T = 6–20 K). The WISE conductor was connected to a power supply with a maximum current of 75 kA. Current tests were conducted to confirm the maximum allowable current, assess its robustness against repeated current applications, identify the critical current, and observe various physical phenomena.

3. Experimental Result

In this section, the experimental results of the WISE conductor are presented. The maximum current-carrying capacity of the WISE conductor was verified under the conditions of T = 6 K and B = 8 T, and its robustness under repeated current application was further tested. In addition to confirming the performance of the conductor, the behavior of the voltage, which is of physical interest, is also presented.

3.1 Durability and performance evaluation of HTS conductors under high current and repeated energization tests

Figure 3 shows the time evolutions of the sample current (I_{sample}) up to 40 kA, the electromagnetic force F, the total voltage V_{tot}, and the temperature T_{center} under the conditions of T = 6 K and B = 8 T. The maximum current of 40 kA is determined due to the limitation of the capacity of the current lead. Throughout the energization process, no instances of quenching, unexpected voltage increases, or temperature increases were detected. At the maximum current of 40 kA, the engineering current density (j_e) corresponds to j_e = 31 A/mm^2, and the conductor is subjected to electromagnetic force



Specification	Value
Maximum Applied Magnetic Field	9 T
Temperature Range	4 to 65 K
Maximum Current	17 kA

Fig. 2. Large Conductor Testing Facility with installed WISE conductor. Magnetic field profile is shown beside facility on the same space scale.

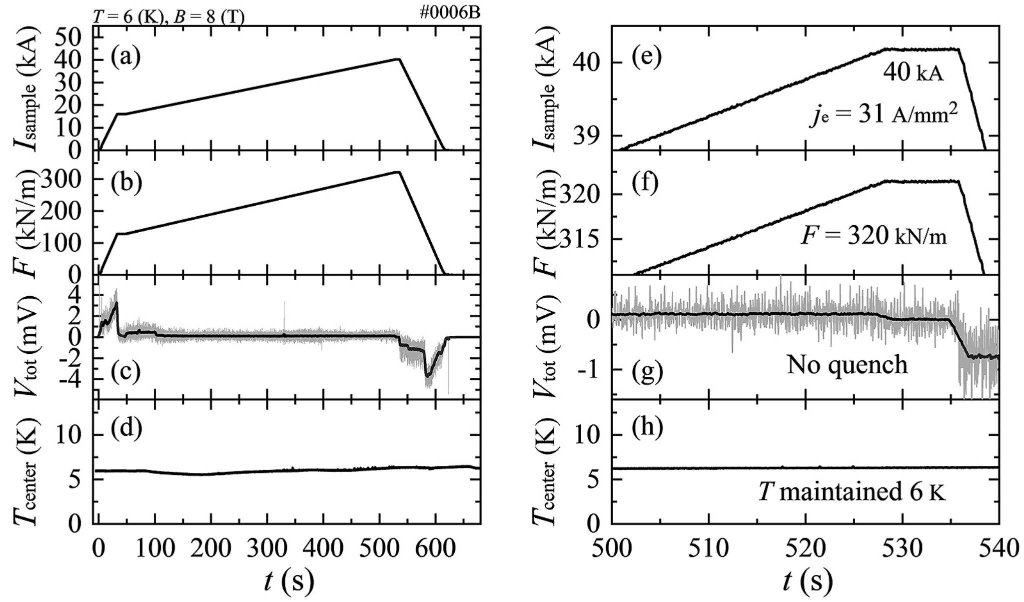


Fig. 3. Time (t) evolution of (a) sample current I_{sample}, (b) electromagnetic force F, (c) total voltage V_{tot} (the black and grey lines indicate smoothed data and raw data, respectively), and (d) temperature T_{center} under the conditions of B = 8 T and T = 6 K. Zoomed-in views of the period between 500 s and 540 s are shown in (e)–(h).

F = 320 kN/m. The conductor exhibits no degradation in durability under the influence of this electromagnetic force. As shown in the right column (Figs. 3(e)–(h)), during holding for 8 s, V_{tot} decreased to 0 (Fig. 3(g)), which means that superconductivity was realized.

During the ramp-up of the current, interesting behaviors of the voltage were observed. As shown in Fig. 4, the current increased at a ramp-up rate of 500 A/s from t = 0 to 32 s, reaching I_{sample} = 16 kA, and total voltage V_{tot} increased to 3.3 mV. After holding, the I_{sample} was further increased to 40 kA at a rate of 50 A/s. Between t = 48 and 100 s, a significant voltage was observed that increased from V_{tot} = 0.38 to 0.46 mV with a single spike at t = 71 s. Subsequently, at approximately t = 100 s, the V_{tot} suddenly decreased to 0.11 mV and then maintained a nearly constant voltage as shown in Fig. 4(c).

In the context of operating magnets for fusion reactors, it is important to ensure the integrity of the conductor by not only verifying the maximum current value but also by ensuring robustness against repeated energization. For helical fusion reactors, the primary requirement for HTS conductors is their ability to withstand repeated energization. Consequently, under the conditions of B = 8 T and T = 20 K, a maximum current of 22 kA, a current change rate of 500 A/s, and 97 cycles of repeated energization were conducted over 164 min, as shown in Fig. 5. Similarly to the 40 kA energization, throughout this energization process, no quench event occurred, unexpected voltage increases, or temperature increases were detected. This indicates that the WISE conductor is capable of withstanding repeated energization and possesses sufficient performance for use in the magnets of helical fusion reactors, which operate in a fundamentally steady-state mode, even though the WISE conductor is simply a stack of HTS tapes.

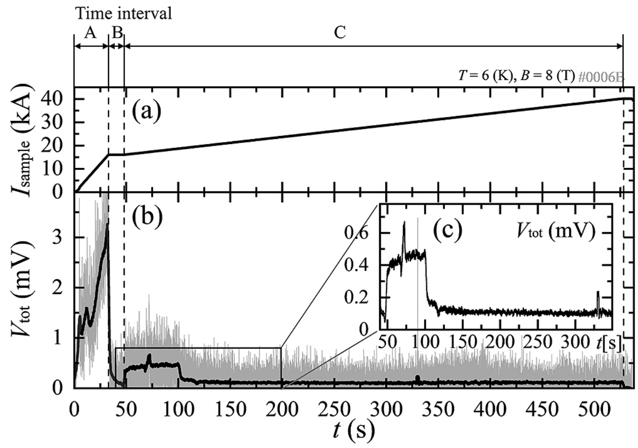


Fig. 4. Time evolution of (a) I_{sample}, (b) V_{tot}, and (c) enlarged view of V_{tot} (smoothed data). Dashed vertical lines indicate time intervals with A, B, and C.

For tokamaks, the requirements for HTS conductors are more complex, involving not only repeated energization but also addressing various issues such as significant induced-electromagnetic forces during plasma current ramp-up and large electromagnetic forces during disruptions. Various types of conductors have been developed to address these challenges [11, 12]. Additionally, while tokamaks experience significant induced-electromotive forces in the magnets during plasma current ramp-up, helical plasmas do not, as they require no plasma current. Furthermore, tokamaks are subject to large electromagnetic forces in the disruptions [13], but helical plasmas are inherently free from such disruptions [14], thus eliminating these concerns. Therefore, in helical fusion reactors, degradation or concerns due to repeated energization of HTS magnets are considered minimal.

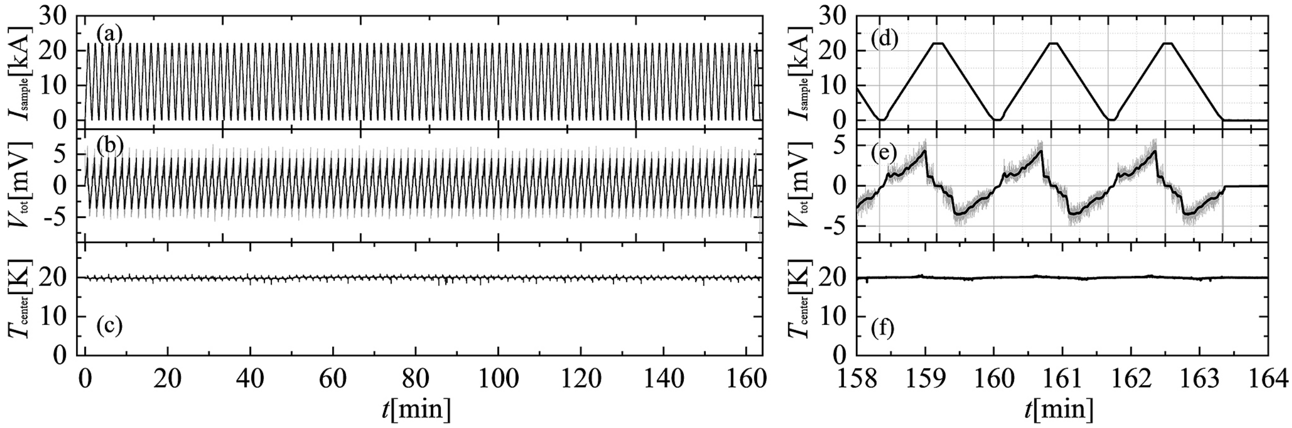


Fig. 5. Waveforms of 97 repeated tests at 20 K and 8 T. (a) I_{sample}, (b) V_{tot}, and (c) T_{center}. Enlarged views are shown in (d)–(f).

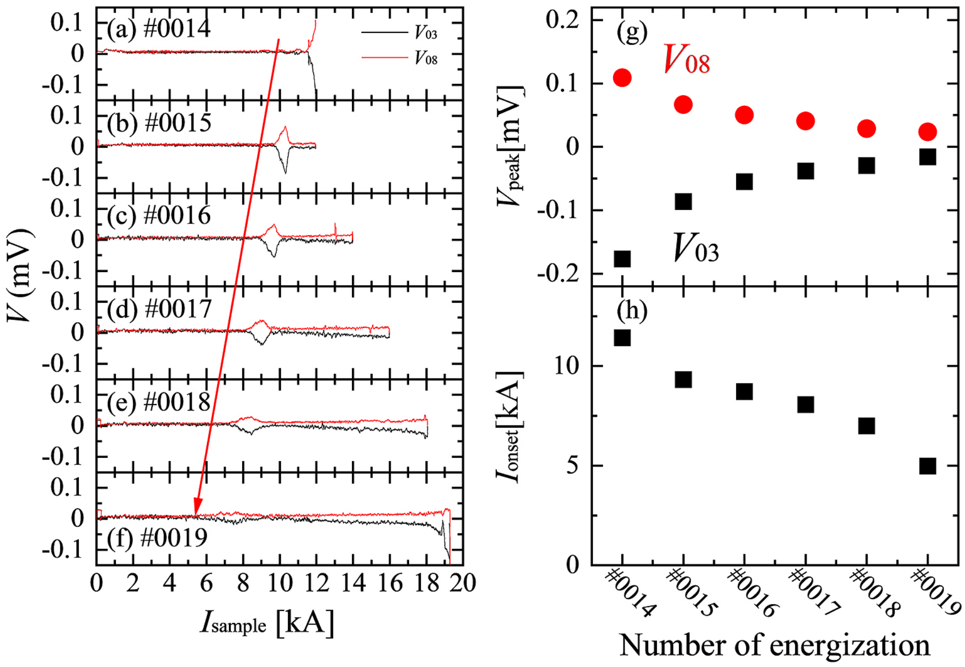


Fig. 6. (a)–(f) I_{sample} – V curve. The voltages (V_{03} and V_{08}) are measured locally. Trends in (g) voltage and (h) onset I_{sample} for each energization.

3.2 Insights into the behavior of local voltages during HTS conductor energization

Prior to these energization tests, a preliminary one was conducted. During these tests, interesting voltage behaviors were observed. Figure 6 shows the relationship between the I_{sample} and local voltages V03 and V08 at the position shown in Fig. 1(b). The conditions are B = 8 T and T = 20 K. In energization test #0014, a rapid increase in voltage was observed around I_{sample} = 11 kA, leading to the determination of a quench and the forced interruption of the test. In the subsequent test (#0015), when the current was reapplied, the voltage increased to around 10 kA but then spontaneously decreased. With each repeated energization, the maximum voltage and I_{sample} value decreased. This is summarized in Fig. 6 (right). Note that the voltage in test #0014 was the maximum value observed immediately before the forced interruption of the current. It can be seen that the voltage is suppressed with each subsequent energization, indicating a training effect.

4. Discussion

The behavior of the voltage during 40 kA energization is examined. As shown in Fig. 4, variations in the voltage were observed during the current ramp-up phase. The ramp-up rate at each time segment is summarized in Table 1. Here, the time intervals are divided for convenience, with each labeled A, B, and C for distinct periods.

In the time interval C, where the current exhibits a steady increase at a slower rate compared to other intervals,

Table 1. Current ramp-up rate at each time segment.

Time interval	Time [s]	dI_{sample}/dt [A/s]
A	0–33	500
B	33–48	0
C	48–528	50

the current increase rate remains constant. This implies that the voltage induced by the change in current (determined by the inductance L and the rate of change of current (LdI/dt)) also remains constant. However, between t = 48 and 100 s, a significant voltage variation was observed, increasing from V_{tot} = 0.38 to 0.46 mV, with a notable spike at t = 71 s, as shown in Fig. 4(c). Subsequently, at approximately t = 100 s, V_{tot} abruptly decreased to 0.11 mV and then stabilized at an almost constant voltage. These voltage behaviors are attributed not only to the contribution of the current change but also to the change in the inductance ($I_{sample}\, dL/dt$).

In the time interval A, a non-constant voltage was also observed, which is similarly thought to include the contribution of the inductance change. This suggests that the REBCO tape moved within the conductor due to the electromagnetic force experienced during the current flow. The electromagnetic force acts on the conductor, causing the REBCO tape to shift its position. The spontaneous decrease in voltage at approximately t = 100 s without external control is attributed to the cessation of movement of the REBCO tape. This stabilization of the voltage indicates that the tape has settled into a stable position. The spike-like voltages observed around t = 71 and 330 s are also considered to be due to the momentary movement of the tapes, potentially caused by transient electromagnetic forces.

Next, voltage generation and mitigation are examined. To understand voltage mitigation, the behavior of the resulting magnetic flux was analyzed. The magnetic flux was estimated by the time integration of the voltage, as shown in Fig. 7. Although the peak voltage decreased with each energization (Fig. 6 (right)), the magnetic flux remained constant as shown in Fig. 8. This implies that although the movement range of the REBCO tape did not change, the rate of change was reduced. Consequently, it is inferred that the voltage generated by the training effect decreased.

For these phenomena, a hypothesis can be proposed that the observed voltage is due to changes in magnetic flux as the tape moves within the magnetic field, rather than from a temperature rise caused by frictional movement. The former can occur without an increase in temperature, while the latter requires it. Ideally, REBCO tapes should be fully impregnated with low-melting-point metals, but voids may exist due

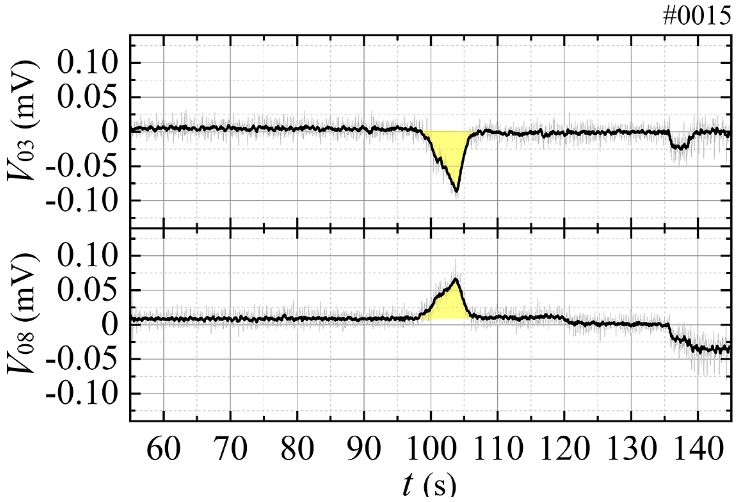


Fig. 7. Estimation of equivalent magnetic flux calculated by integrating voltage over time. The hatched regions correspond to the integrated areas.

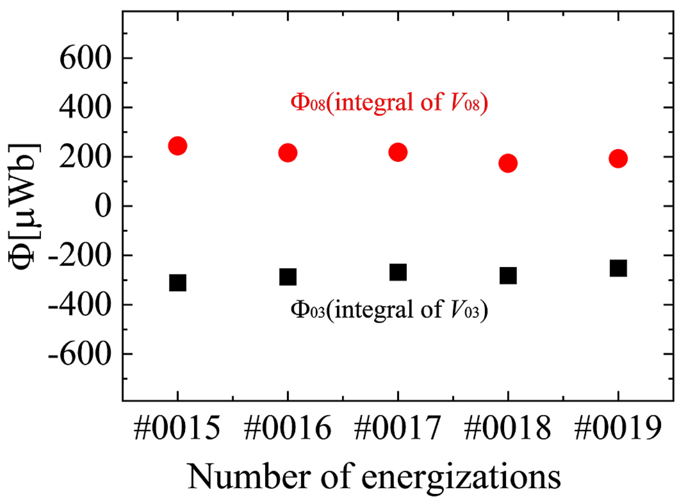


Fig. 8. Trend of equivalent magnetic flux.

to atmospheric impregnation. These voids, around tens of micrometers in size, could account for the magnetic flux value of $\Phi = 250$ μWb shown in Fig. 8. This would require an area of 31.3×10^{-6} m^2 in an assumed magnetic field of 8 T, corresponding to a movement of approximately 31 μm, which is a plausible value.

5. Summary

This study explores the potential applications of simply-stacked REBCO tape conductors in helical fusion reactors. The HTS conductor integrates several innovative concepts, including post-shaping impregnation and reinforcement through armor blocks. The conductor successfully achieved a current of 40 kA under $B = 8$ T at $T = 6$ K while maintaining its superconducting state, without exhibiting normal resistance. The induced voltage was suggested to comprise both dI/dt and dL/dt components. Furthermore, a total of 97 cycles at 22 kA with a ramp rate of 500 A/s was conducted at $B = 8$ T and $T = 20$ K, with no observed degradation or quench. These findings demonstrate the conductor's potential for application to helical magnets. The study also identified a transient voltage rise during the increase of I_{sample}, which was mitigated with each subsequent energization cycle, suggesting conservation of magnetic flux and potential deviations in the REBCO tape or current path.

Further testing is required to evaluate the WISE conductor's performance under FFHR-b3 conditions (20 K, 19 T). Currently, evaluations are limited to 8 T due to equipment constraints. Future plans include establishing facilities for higher magnetic field testing and collaborating with other institutions. These efforts aim to provide a more accurate assessment of the WISE conductor's behavior under actual operating conditions.

Acknowledgments

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