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Self-field measurements of an HTS twisted stacked-tape cable conductor

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Abstract
For a twisted stacked-tape cable (TSTC) conductor composed of REBCO tapes, self-field measurements were conducted with Hall sensors. In the measurements, a 650 mm diameter single turn coil wound with the TSTC conductor, which was made with 48 REBCO tapes whose width was 6 mm, was utilized as a test sample. Based on the measurement results, the current distribution of the TSTC conductor was investigated with analytical models. The analytical results indicate the current distribution of the TSTC is uniform under the condition that the operating current is 10 kA and the sample temperature is approximately 30 K. On the other hand, the current distribution is not uniform at the excitation and the degauss of the TSTC conductor with the ramp rate of 50 A/s.

Keywords:
Magnetic field measurement, REBCO tape, twisted-stacked tape cable, current distribution

1. Introduction

Various large current-carrying conductors composed of REBCO tapes have been proposed in recent years for high current applications such as magnets and power transmissions [1-6]. As one of the conductors, a twisted stacked-tape cable (TSTC) is being developed at the Massachusetts Institute of Technology [7-10]. The TSTC conductor is composed of stacked REBCO tapes which are twisted along the longitudinal direction of the stacked tapes. The stacked REBCO tapes are immersed with a solder, and are imbedded in a copper former. Therefore, current transfer between REBCO tapes occurs easily when applying current in the TSTC conductor. In this study, self-field measurements of the TSTC conductor were conducted in order to investigate current distribution in the conductor. As a test sample, a 650 mm diameter single turn coil of a TSTC conductor was utilized. The current distribution in the TSTC conductor is discussed by using analytical models with the measured self-fields.

2. Sample

The sample is composed of a TSTC conductor mounted in a G10 holder. The conductor has a hendecagon shape, the diameter of which is 650 mm. In the hendecagon shape, the conductor is bent at each half twist pitch, which is 180 mm. Figs. 1 and 2 illustrate the three-dimensional configuration of a TSTC conductor in the sample and the top-view of the configuration, respectively. Details of the winding method with the TSTC are described in Ref. [8]. At the termination, the TSTC is mounted on copper plates with a solder. Details on how the termination was assembled and prepared are described in Ref. [10]. The cross-section of the conductor is shown in Fig. 3. The conductor is composed of the TSTC, which consists of 48 SuperOx REBCO tapes whose width is 6 mm, mounted in a copper former with a copper braided sleeving. The REBCO tape is copper-stabilized, and the details of the tape are listed in Table 1. Solder is used at the gap between the REBCO tapes and at the gap between the TSTC and the copper former. The conductor is mounted in a copper U-channel and is attached to coolant channels. The TSTC is cooled through the coolant channels. Voids in the copper U-channel are filled with solder.

3. Experimental setup

Energization tests of the sample were conducted using the 13 T test facility of the National Institute for Fusion Science (NIFS) [11, 12]. The sample was installed into a vacuum vessel located in a bore of an external field coil. And the terminations of the sample were connected to bus-bars composed of REBCO tapes and copper plates. Fig. 4 shows a photograph of the sample with the bus-bars. In the sample, the conductor was cooled by helium gas, the temperature of which could be controlled from 4.4 K to approximately 50 K. The Cernox thermometer was set on the conductor to control the conductor temperature. The position of the thermometer is shown in Fig. 2.

To measure self-fields generated by the conductor, Hall sensors were arranged on the sample. Fig. 5 shows the layout of four Hall sensors B1, B2, B3, and B4 with the cross-section of the sample. The position of the Hall sensors in the top view is shown in Fig. 2. The model reference of the Hall sensors was F.W. BELL BHT921, and the sensors were calibrated. Using the Hall sensors, self-fields in the y-direction were measured. As for the alignment error of the Hall sensors, approximately 2 mm with the reference to the center of the TSTC is considered the maximum error.

4. Measurements

4.1 Trapezoidal current waveform

Self-fields of the sample were measured when the sample was energized with a trapezoidal current waveform and the sample temperature was controlled at 34 K. Fig. 6 shows the measurement results. The sample was energized up to 10 kA with the ramp rate of 50 A/s, and was degaussed with the ramp rate of 50 A/s after holding 10 kA for 300 sec. No external magnetic field was generated for the sample. As shown in Fig. 6, the measured self-fields are linear to the sample current. The influence of shielding currents in the TSTC conductor was not observed in the change of the sample current. The measurement results indicate that an HTS TSTC conductor can generate a stable magnetic field. In Section 5, the current distribution of the sample in the trapezoidal current waveform is discussed.

4.2 Increase of sample temperature under constant sample current

Self-fields of the sample were measured while increasing gradually the sample temperature from 29.5 K to 33.5 K when a sample current was fixed at 10 kA. Figs. 7 and 8 show the measurement results of the sample current and self-fields with the sample temperature, respectively. During the increase of the sample temperature, self-fields were stable at each Hall sensor. The measurements indicate that several degrees of change in sample temperature does not have an influence of current distribution in the TSTC under the condition that the sample current is 10 kA and the sample temperature is approximately 30 K. Based on the measurement results, the current distribution of the sample is discussed in Section 5.

5. Discussion

5.1 Uniform current model

To investigate the current distribution of the sample, a two-dimensional magnetic field calculation was conducted using an analytical model. The analytical model is composed of a cross-section of the TSTC whose current distribution is uniform. In this model, the position of the TSTC and Hall sensors are fixed, based on the experimental setup shown in Fig. 5. Fig. 9 shows the measurement and the calculation results of self-fields when the sample current is 10 kA. The measurement results are self-fields at each Hall sensor, which are the results at 300 s in Fig. 6. And the calculation results are self-fields along the y direction at z = 36 mm. As shown in Fig. 9, the measurements are in good agreement with the calculations. The analytical result indicates that the current distribution of the TSTC is uniform when the sample current is maintained at 10 kA and the sample temperature is controlled at 34 K.

5.2 Line current model

From the measurements of self-fields shown in Fig. 8, the current center in the TSTC conductor was analyzed using a line current model. This model is composed of one line current whose length is infinite [13]. The current value of one line is equivalent to the transport current of the TSTC conductor. The positions y and z were used as a parameter in the investigation of the line current position. The y direction and the z direction show the tape width direction and the tape stacking direction, respectively. The position where y is 0 m and z is 0 m is the geometric center position in the cross-section of the TSTC. The line current position was specified so as to minimize the sum of the squared self-field difference ΔB_n between the measurement result B_n and the calculation result B_n^* at each position of the Hall sensors in the y-direction, which is

$$\Delta B_n = B_n - B_n^* \qquad (1)$$

where n is the number of the Hall sensors.

$$min\left\{\sum_{n=1}^{4} \Delta B_n^2\right\} \qquad (2)$$

In this model, we assume that the current distribution of the TSTC is uniform when the position of the line current is at or near the center of the TSTC's cross-section.

Figs. 10, 11, and 12 show the positions of the current center in the TSTC conductor under the trapezoidal current waveform shown in Fig. 6. In Fig. 10, the plots indicate current center positions at each time during the excitation. The current center moved irregularly in the middle of the tape width direction and in the minus range of the z direction. The current center positions when holding the sample current of 10 kA are shown in Fig. 11. The center positions at each time are close to the geometric center position in the cross-section of the TSTC. Fig. 12 shows the current center position at each time during the degauss. The current center position at each time moved largely in the tape stacking (z) direction. The movement of the center position is small in the tape width (y) direction, compared to the movement in the tape stacking direction. From the analytical results of current center positions in the TSTC, the current distribution of the TSTC will be uniform when holding a sample current of 10 kA. On the other hand, the current distribution will be non-uniform at the excitation and the degauss of the sample, provided that the current distribution may become temporarily uniform during the excitation.

Fig. 13 shows the positions of the current center in the TSTC conductor at 0 s, 200 s, 400 s, 600 s, and 800 s during the increase of the sample temperature at the operating current of 10 kA shown in Fig. 8. The current center positions at each time are close to the geometric center, which is the same as the positions shown in Fig. 11. The analytical results indicate that the current distribution of the TSTC is stable and uniform when the operating current is 10 kA with an increase of the TSTC temperature from 29.5 K to 33.5 K.

6. Conclusion

Self-field measurements of a single turn coil wound with a TSTC conductor were conducted using Hall sensors. Based on the measurement results, the current distribution of the TSTC conductor was analyzed using analytical models. The analytical results indicate that the current distribution of the TSTC is uniform when the operating current is maintained at 10 kA and the temperature is controlled at 34 K. On the other hand, the current distribution is not uniform at the excitation and the degauss with the ramp rate of 50 A/s, provided that the current distribution may become temporarily uniform during the excitation. Additionally, the current distribution of the TSTC is stable and uniform when the temperature is increased from 29.5 K to 33.5 K at the operating current of 10 kA.

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Table 1 Details of REBCO tape

Width	6 mm
Substrate material	Hastelloy C276
Thickness of substrate	63±3 μm
Thickness of silver layer	2 μm
Surround copper layer	20 μm per side
Minimum Ic at 77 K, s.f [a]	200 A

[a] s.f：self-field

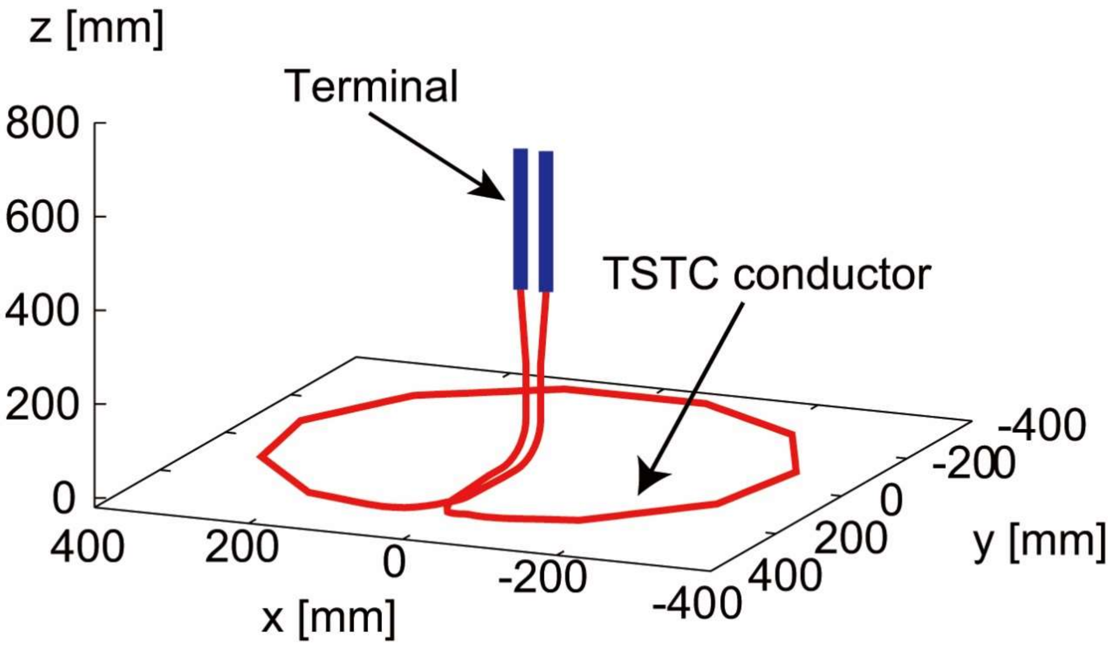

Fig.1 Configuration of the TSTC conductor.

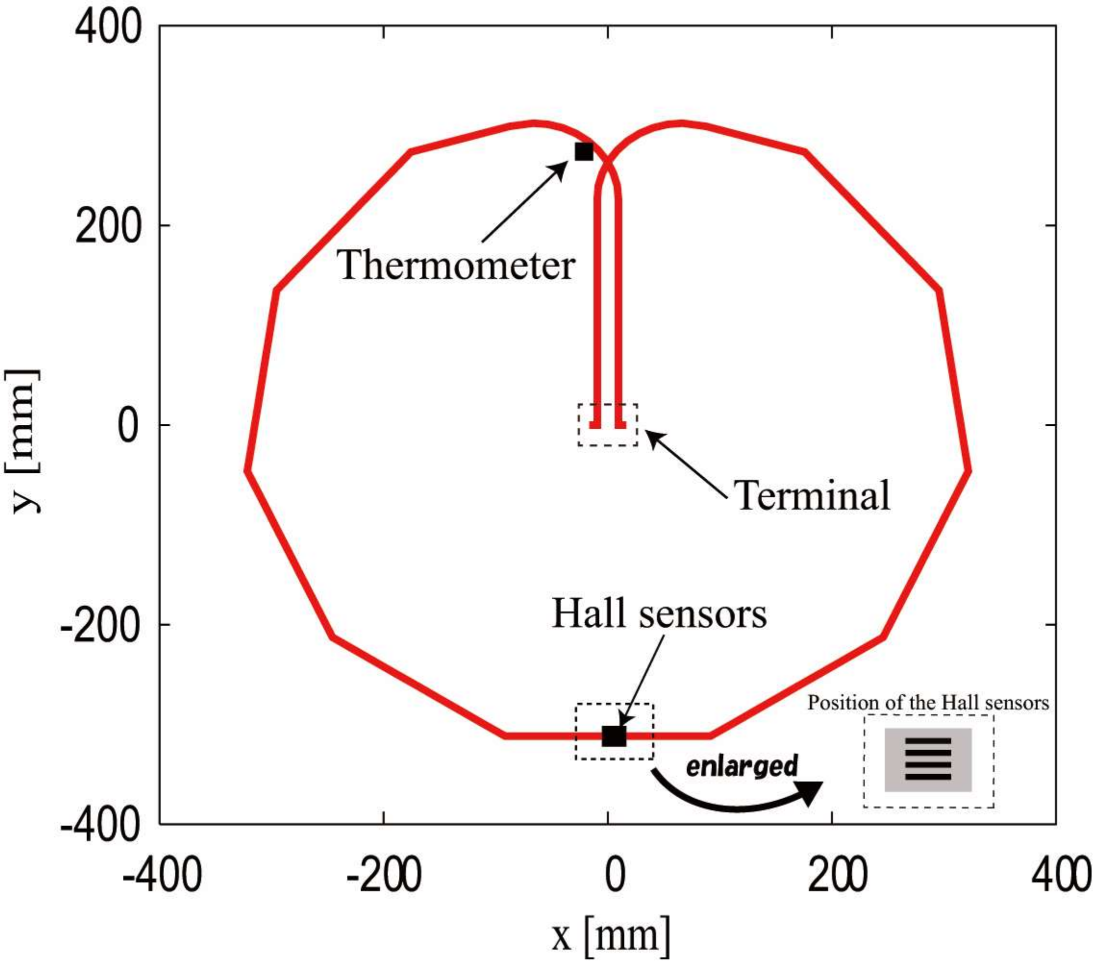

Fig.2 Top view of the TSTC conductor with four Hall sensors and a thermometer.

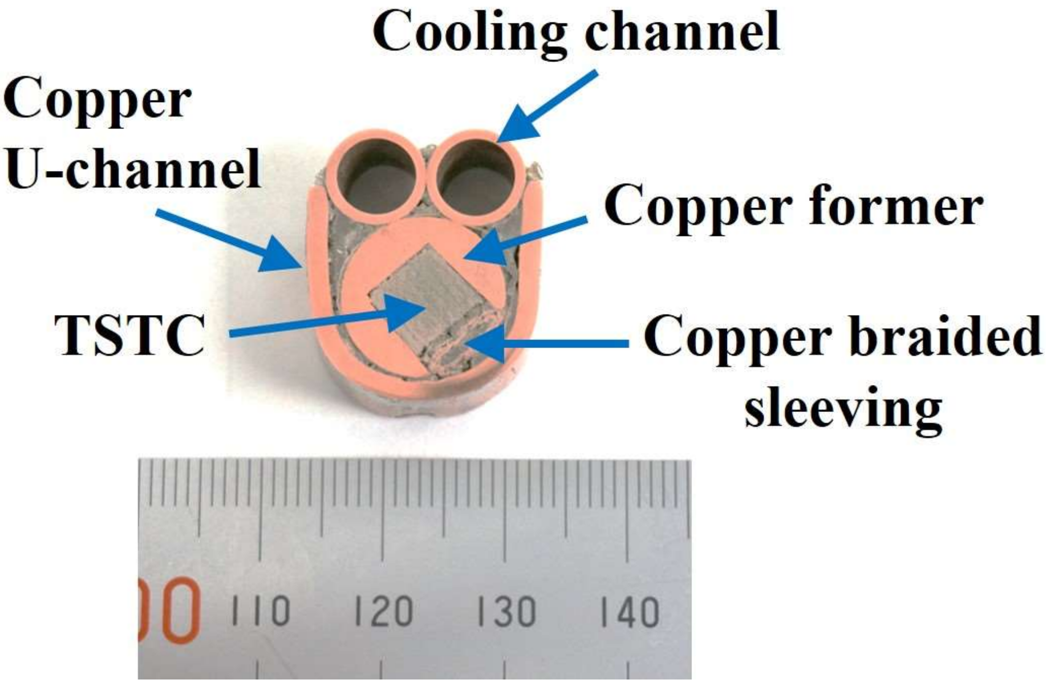

Fig.3 Cross-section of the TSTC conductor.

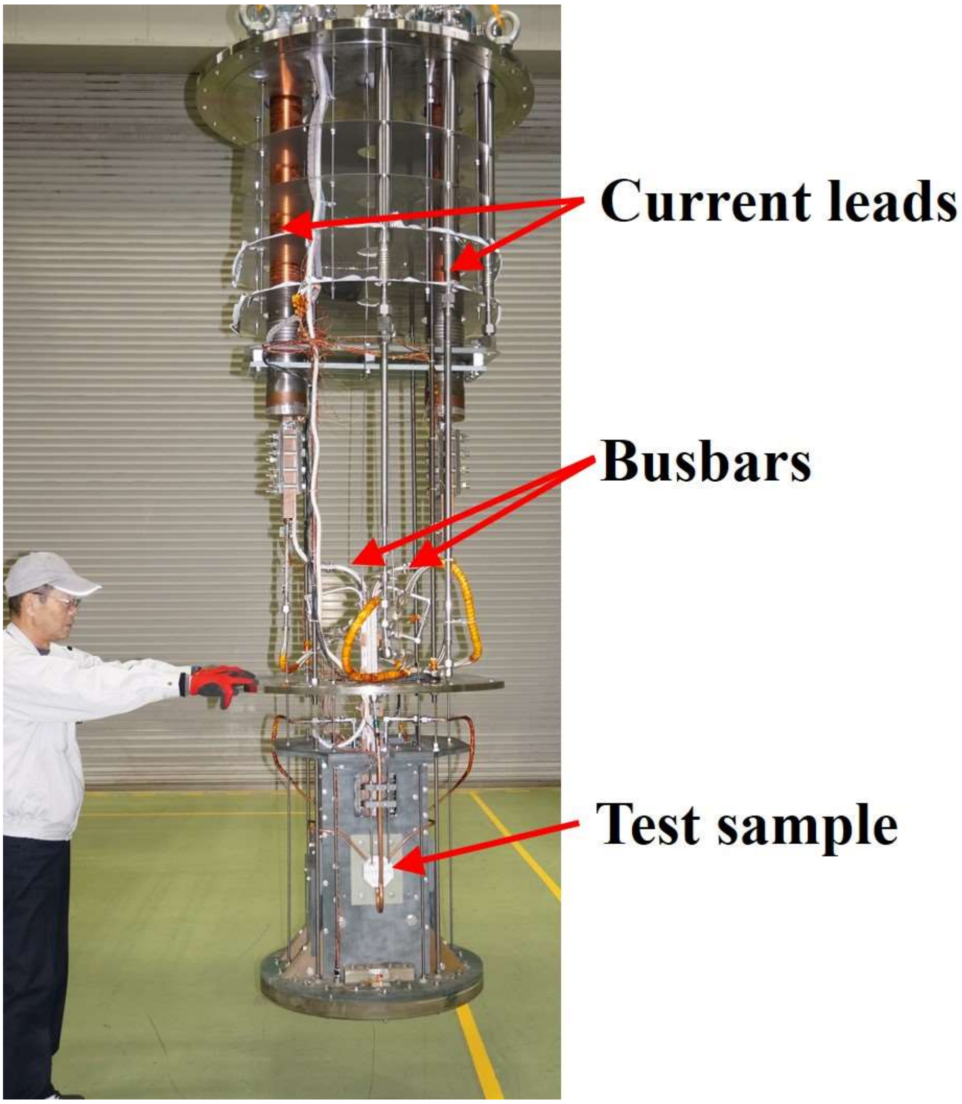

Fig.4 Photograph of the test sample with busbars.

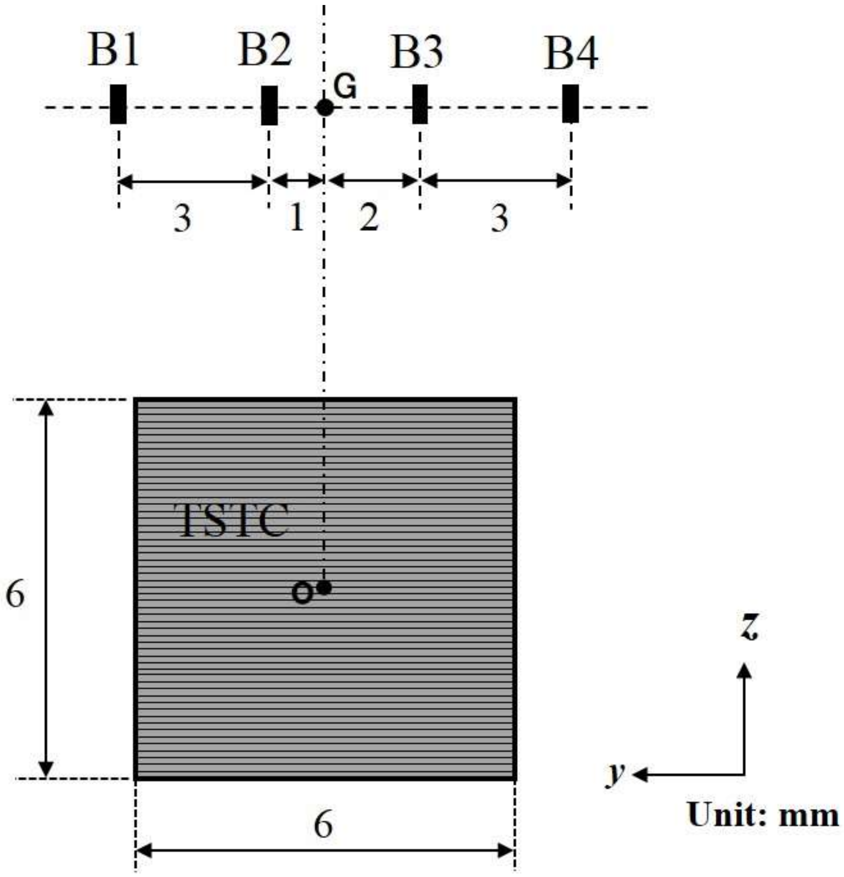

Fig.5 The positions of Hall sensors and the TSTC. At this cross-section of the TSTC, the tape stacking direction is the *z*-axis and the tape width direction is the *y*-axis. In this figure, the position G is as follows: (y, z) = (0 ± 1, 36 ± 1). The unit is mm.

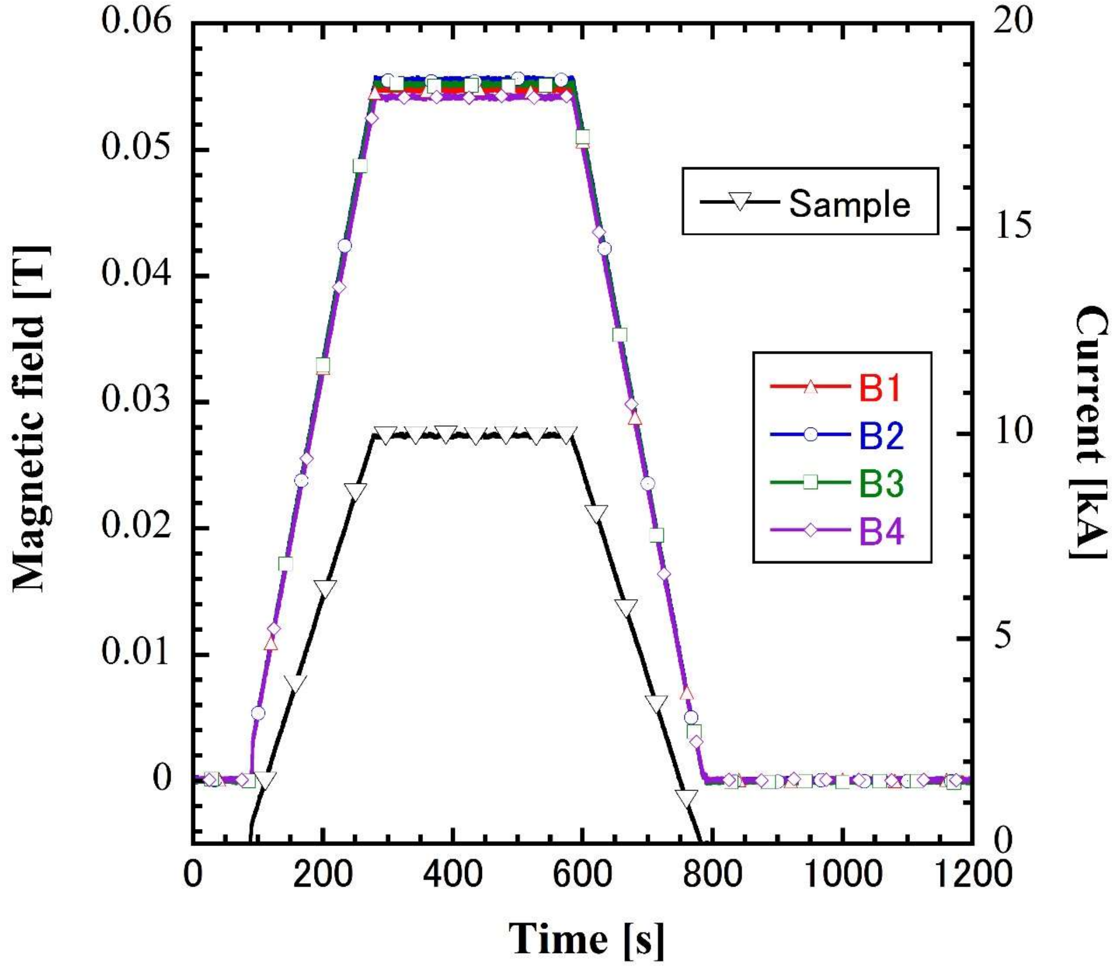

Fig.6 Measurement results of self-fields at the trapezoidal current waveform.

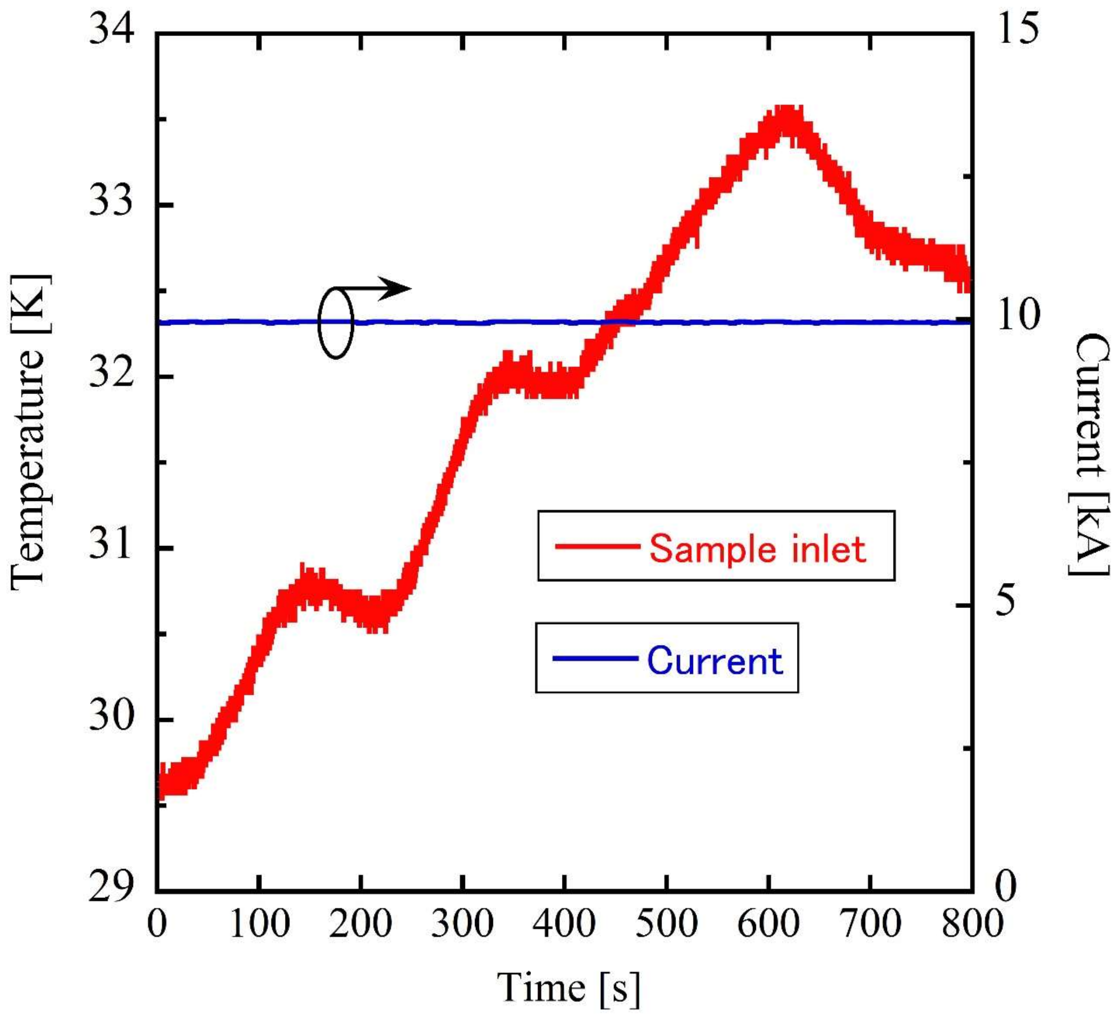

Fig.7 Measurement results of the conductor temperature at the inlet when the conductor current is 10 kA.

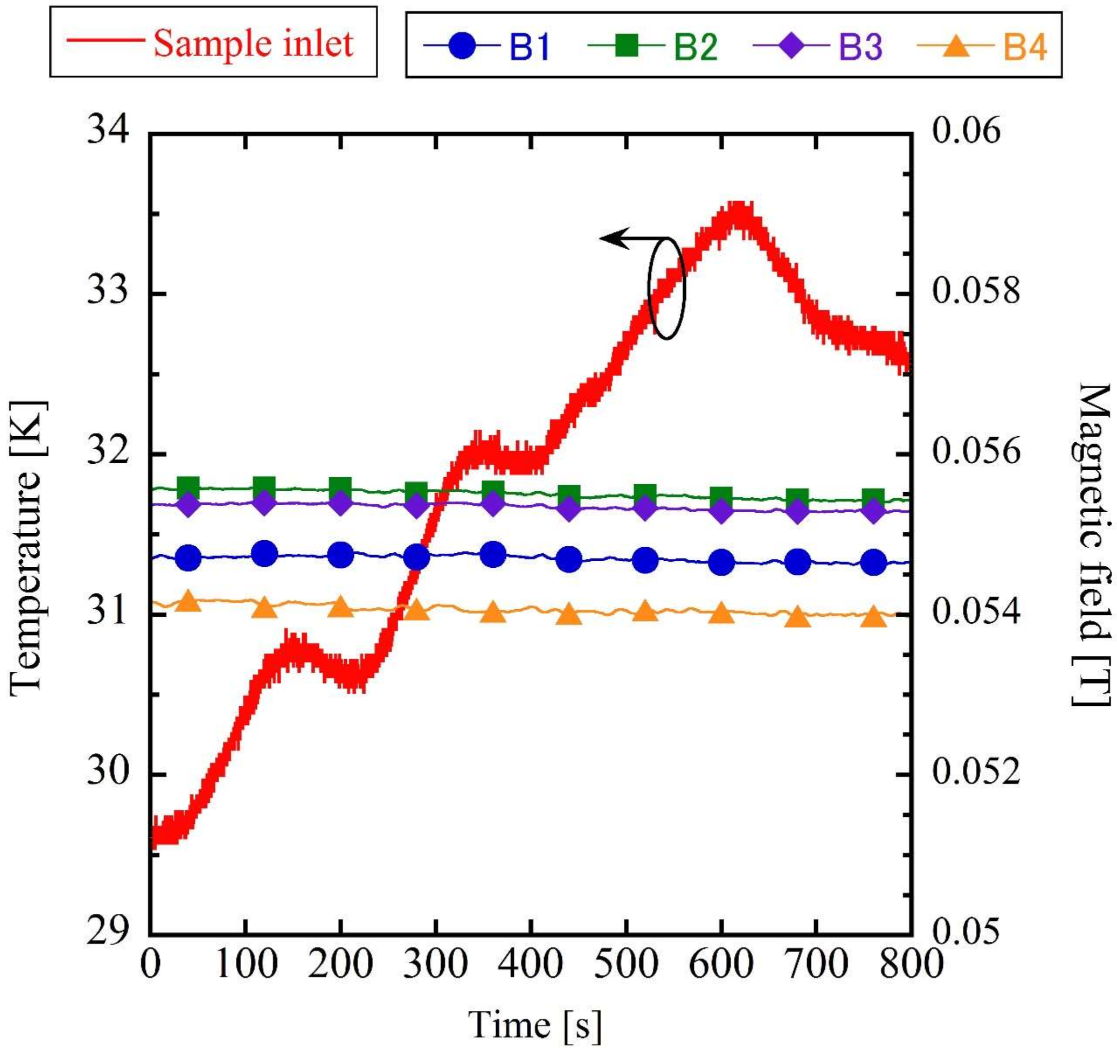

Fig.8　Measurement results of self-fields when the conductor temperature is increased while holding the conductor current of 10 kA.

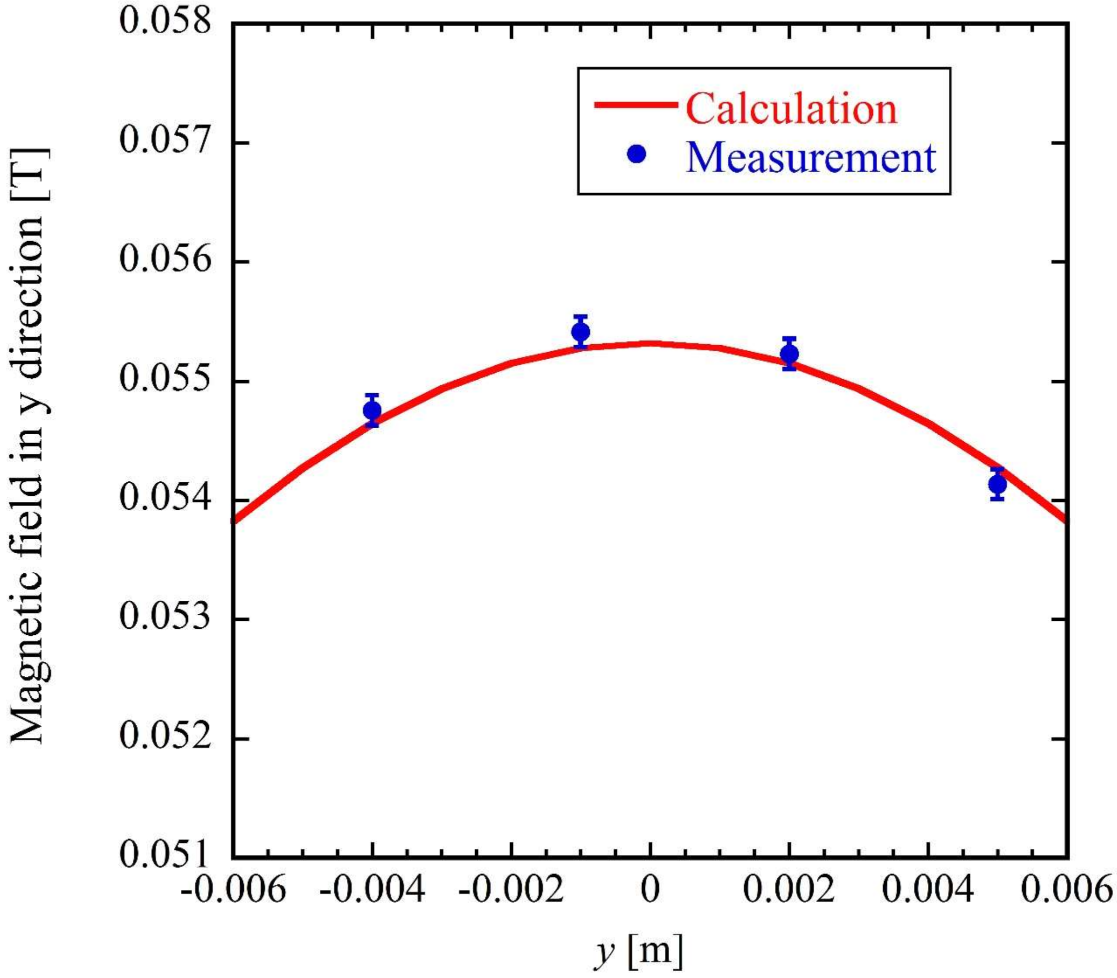

Fig.9 Comparison between measurements and calculations for self-fields when the conductor current is 10 kA.

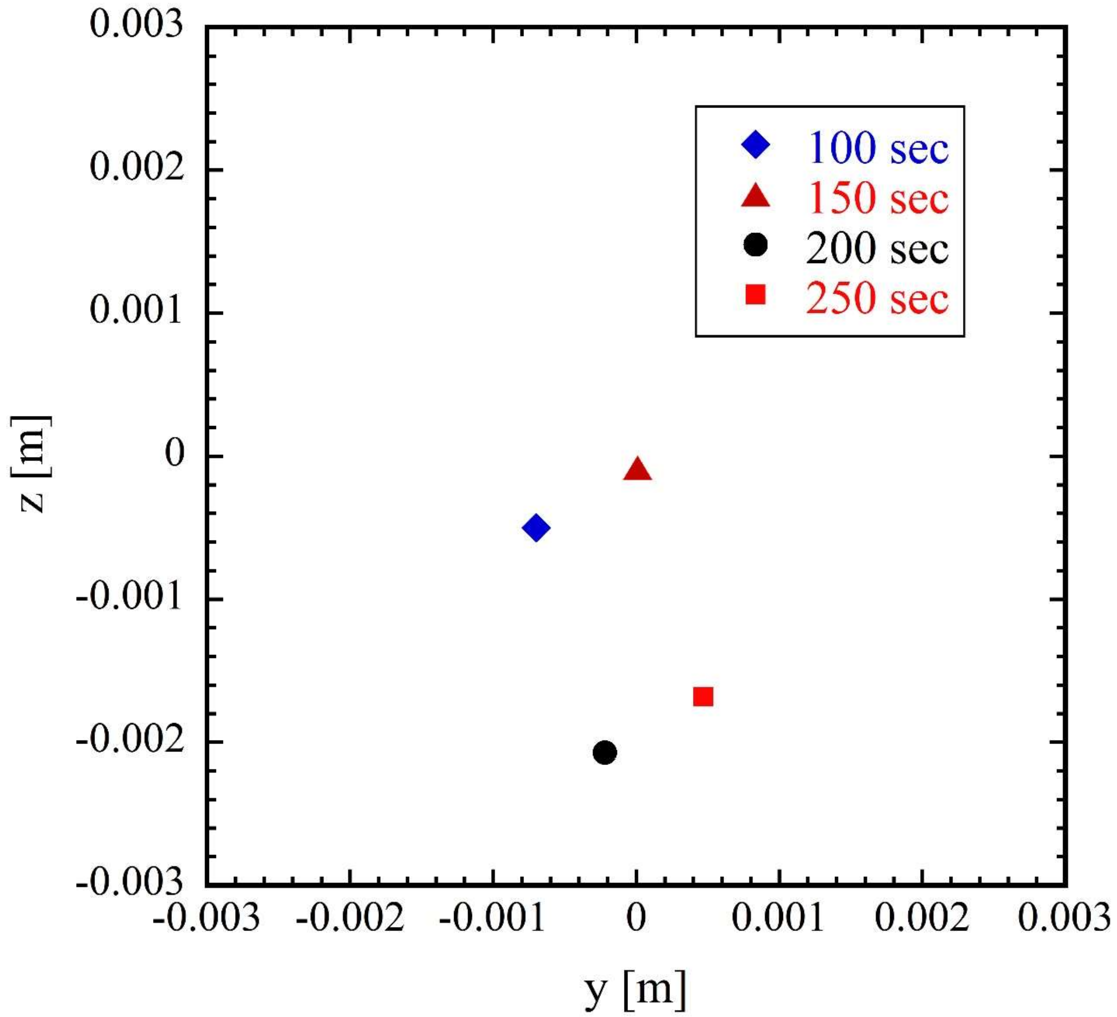

Fig.10 The position of a current center in the TSTC conductor during the excitation of the sample. Plots indicate the current center position at each time.

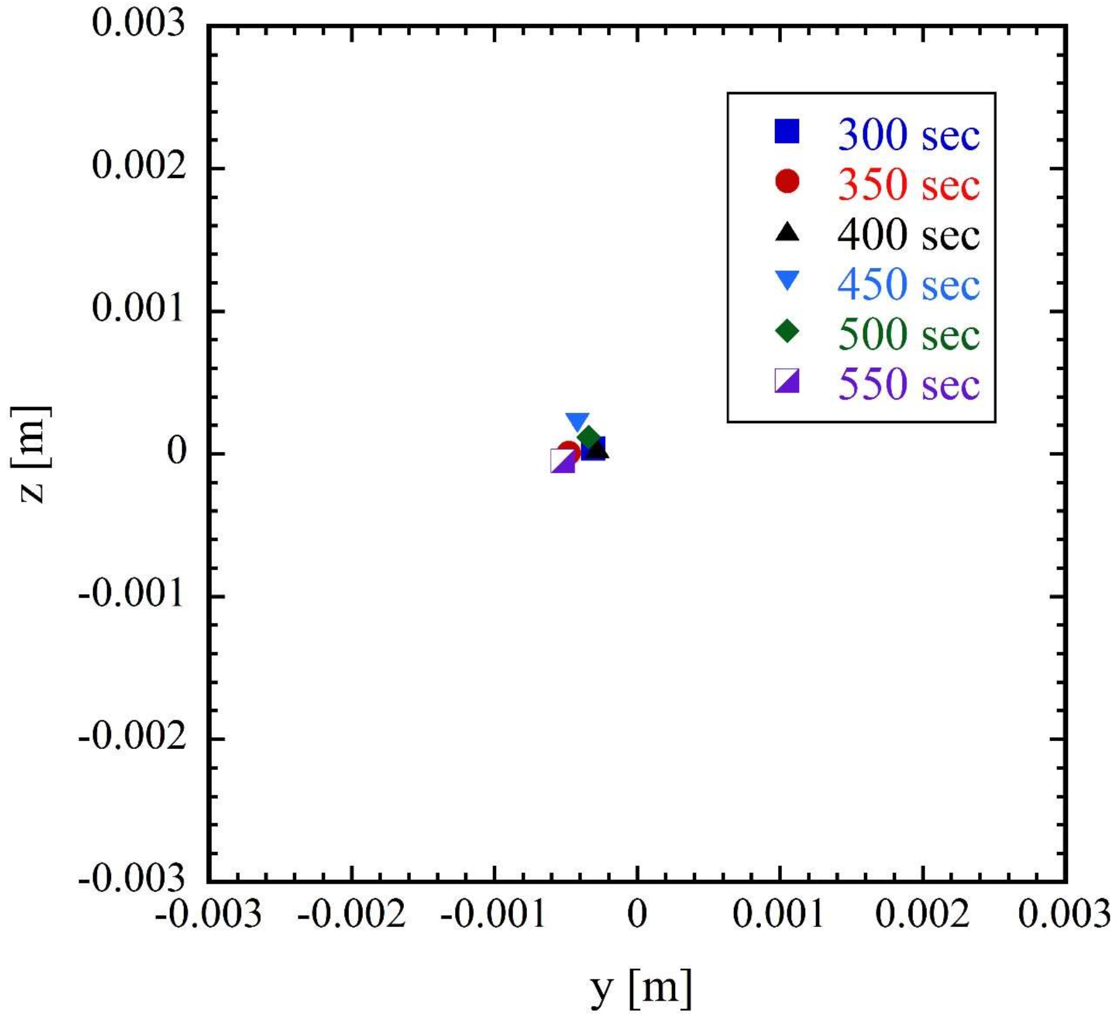

Fig.11 The position of a current center in the TSTC conductor while holding the operating current of 10 kA. Plots indicate the current center position at each time.

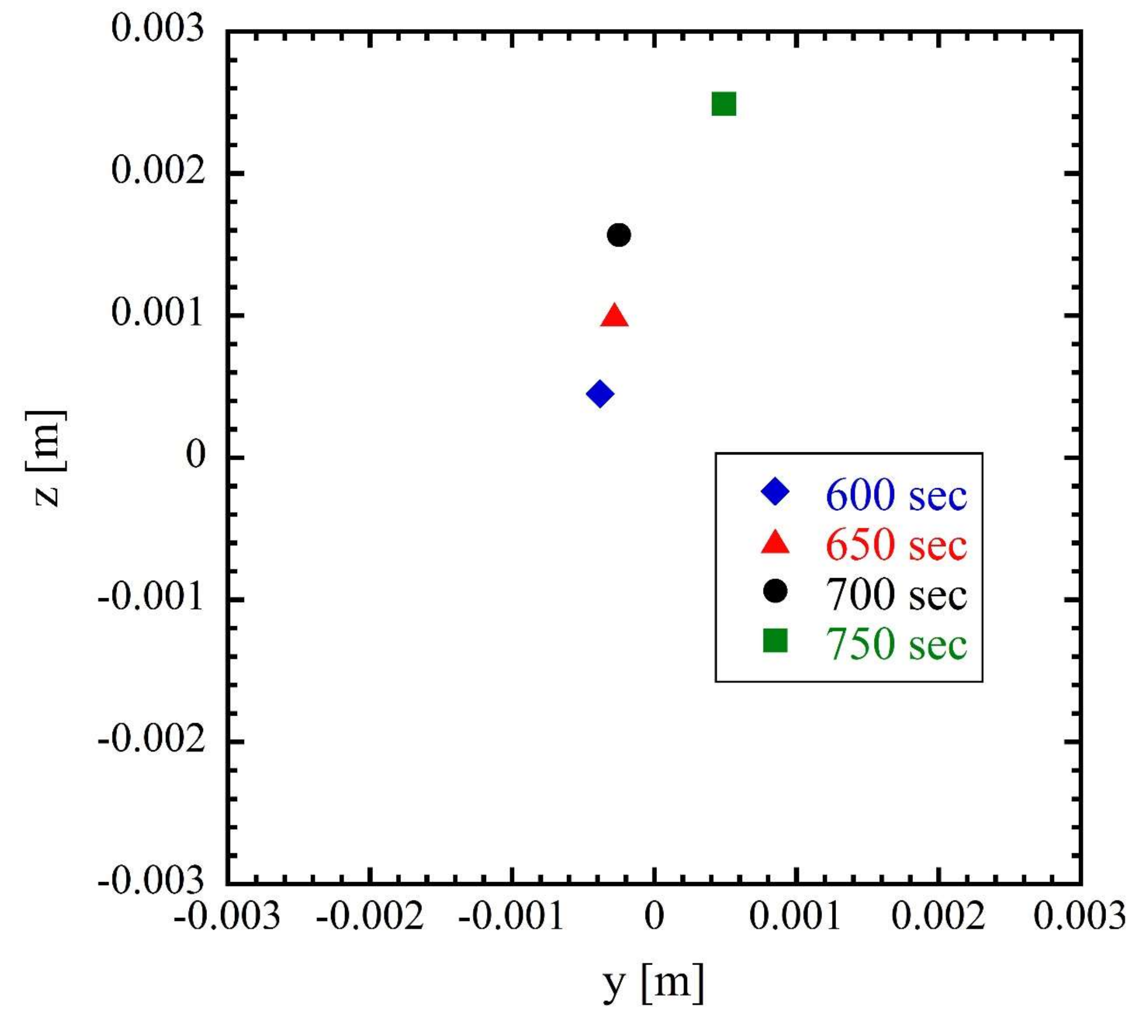

Fig.12 The position of a current center in the TSTC conductor during the degauss of the sample. Plots indicate the current center position at each time.

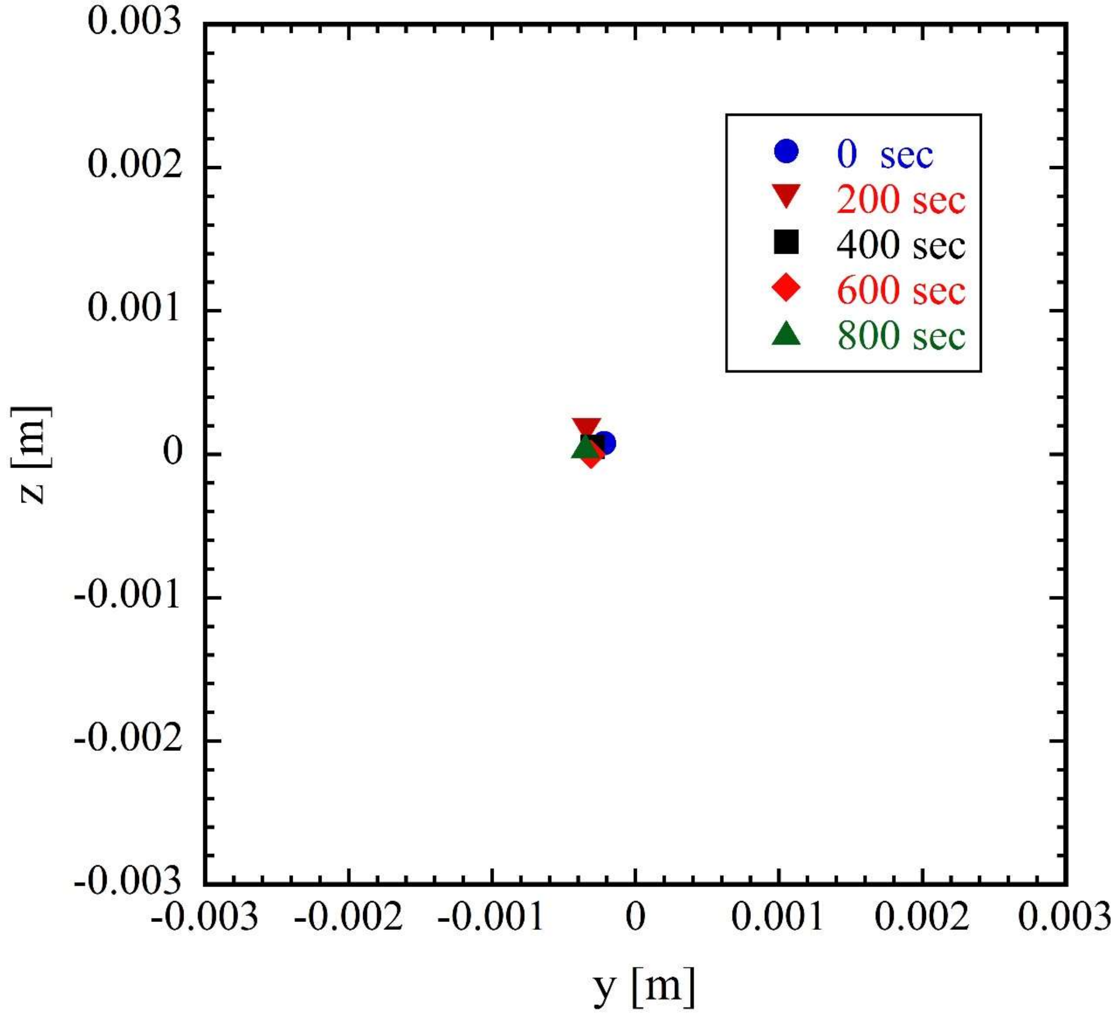

Fig.13 The position of a current center in the TSTC conductor during the increase of the sample temperature at the operating current of 10 kA. Plots indicate the current center position at each time.