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Investigation of long time constants of magnetic fields generated by the JT-60SA CS1 module

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Abstract

In a cold test of the JT-60SA CS1 module, which is composed of six octa-pancake coils and one quad-pancake coil wound with Nb₃Sn CIC conductors, the measurement of self-magnetic fields generated by the CS1 module was conducted. As a result, the decay of the self-magnetic field was observed after the CS1 module was degaussed. The time constant of the decay was from 90 s to 269 s. The measurement results indicate that loop currents with long time constants occurred in the CS1 module due to coil energization. The loop currents with long time constants, which are also called ‘supercurrents’, are irregular coupling currents that are an unexpected phenomenon from the conductor design.

Loop currents with long time constants in CIC conductors have only been observed in large superconducting coils so far. To verify an occurrence of loop currents with long time constants in a CIC conductor without coil winding configuration, self-magnetic fields were measured using a short straight CIC conductor where a multi-strand cable was connected electrically at the conductor ends. As a result, loop currents with long time constants ranging from 57 s to 105 s occurred in the short straight CIC conductor, the length of which is approximately 1 m. The measurement results indicate that the conductor length is not always related to loop currents with long time constants. The occurrence of loop currents with long time constants in the CIC conductor depends on the presence of current paths at the conductor ends.

Keywords:

JT-60SA, Central solenoid, Nb₃Sn, Cable-in-conduit conductor, Magnetic field measurement, Long time constants, supercurrent, irregular coupling current

1. Introduction

The JT-60 tokamak is being upgraded to an advanced superconducting tokamak to be called the JT-60 Super Advanced (JT-60SA) at the National Institutes for Quantum and Radiological Science and Technology (QST) in Japan [1-5]. In the JT-60SA, the magnet system consists of a central solenoid (CS), 18 toroidal field coils, and six plasma equilibrium field (EF) coils. All coils were wound with cable-in-conduit (CIC) conductors. As illustrated in Fig. 1, the CS is composed of four modules, CS1, CS2, CS3, and CS4. In the superconducting coil test facility of the National Institute for Fusion Science (NIFS) [6, 7], a cold test of the CS1 module was conducted before the CS1 module was installed in the magnet system of the JT-60SA. This paper describes the measurement of self-magnetic fields generated by the CS1 module in the cold test. And magnetic fields with long time constants observed in the CS1 module are discussed while comparing the measurements of a CS model coil. In addition, the measurement of self-magnetic fields generated by an EF joint sample are described to investigate the relation between conductor length and the occurrence of loop currents having long time constants in the CIC conductor.

2. JT-60 SA CS1 module

Figs. 2 and 3 show a photograph and the configuration of the JT-60SA CS1 module, respectively. The CS1 module is composed of six octa-pancake coils and one quad-pancake coil [3, 4]. The specification of the CS1 module is listed in Table 1. All coils were wound with a Nb₃Sn CIC conductor composed of 216 Cr-plated Nb₃Sn strands and 108 copper wires. In Table 2, the specification of the CS conductor is listed. Each coil was connected through butt joints [8, 9] of the conductors.

3. Test facility

A cold test of the CS1 module was conducted using a test facility which can accommodate testing of a forced-cooling superconducting coil [6, 7]. The details of the test facility are described in Refs. [6, 7, 10, 11]. The helium cryogenics system of the test facility was upgraded in the 2014 Japanese Fiscal Year [12]. Fig. 4 shows the CS1 module installed in the cryostat of the test facility. The CS1 module was mounted on supporting posts, and was electrically

connected with the current-leads of the cryostat through current feeders composed of NbTi CIC conductors.

4. Magnetic field measurements

4.1 Measurement setup

To measure a magnetic field generated by the CS1 module, Hall sensors were mounted on top of the CS1 module. The model references of the Hall sensors are F.W. BELL BHT 921 and Lake Shore HGCT-3020, and the Hall sensors were calibrated. Fig.3 (b) shows the position of the Hall sensors. These sensors were located at 60°, 140°, 260°, and 340° around the CS1 module. At each angle, the Hall sensors were placed evenly spaced apart in a radial direction as illustrated in Fig. 5. Self-magnetic fields in the axial direction of the CS1 module were measured using the Hall sensors. The axial direction corresponds to z direction in Fig. 5. As for the alignment error of the Hall sensor, about 2° angle with reference to the center of the CS1 module is considered to be the maximum error.

4.2 Results

The CS1 module was energized to 5 kA at a ramp rate of 20 A/s, and then the CS1 module was maintained at 5 kA for 300 sec. The CS1 module was then degaussed at a ramp rate of 20 A/s. During the coil operation, supercritical helium whose temperature was about 6 K was supplied to the CS1 module. Fig. 6 shows the self-magnetic fields in the axial direction at 140° (P2) during the coil operation. The magnetic fields were larger toward the center of the CS1 module during coil energization. Figs. 7 and 8 show the magnetic fields at 140° and 260° after the current of the CS1 module reached to 0 A. Although the current was 0 A, the magnetic fields at each Hall sensor gradually decreased with several time constants. The time constants are listed in Table 3. The range of the time constants was from 90 s to 269 s.

5. Discussion

In large superconducting coils wound with CIC conductors, there are two types of coupling currents. One is the ‘regular’ coupling current which can be estimated by the cabling pattern of a CIC conductor [13, 14]. The other is the ‘irregular’ coupling current which is an unexpected

phenomenon from the conductor design. The ‘irregular’ coupling current is the same as ‘supercurrent’, which flows over the entire cable length, observed in a Rutherford type cable [15]. Regarding a decay time constant after coil excitation and demagnetization, the time constant of the regular coupling current is less than several hundred milliseconds. On the other hand, the time constant of irregular coupling current is much longer than one second.

In this study, a ‘loop current’ is defined as an irregular coupling current with a long time constant which is longer than several hundred milliseconds.

5-1. Comparison between the CS1 module and the CS model coil in terms of magnetic field with long time constants

A model coil was fabricated to verify the process of coil manufacturing and fabrication jigs for the CS1 module [3, 6, 7]. The model coil was wound with a Nb₃Sn CIC conductor which was the same as the conductor used for the CS1 module. The inner and outer diameters of the model coil were the same as the diameters of the CS1 module, but the coil layer of the model coil was different from that of the CS1 module. The model coil was a quad-pancake coil. Fig. 9 illustrates the schematic view of conductor lengths of the model coil and the CS1 module. The conductor lengths of the model coil and the CS1 module were approximately 200 m and 2600 m, respectively. In the CS1 module, as described in Section 2, each pancake coil was connected using butt joint technology where two superconducting cables were connected through a 0.1 mm-thick-copper sheet by diffusion bonding [8, 9]. Therefore, loop currents, which are supercurrents, cannot flow along the entire length of the CS1 module due to the resistance of the butt joint while holding coil current after coil excitation and degauss. As a result, although the conductor length of the CS1 module is much longer than that of the model coil, the time constants of the loop current in the CS1 module are comparable with the time constants in the model coil, which ranges from 17 to 571 s.

5-2. Magnetic field measurements of a short and straight CIC conductor equipped with current terminals

In a coil wound with CIC conductors, the length of which is over several tens of meters, loop currents have been observed in the past [6, 16-21]. On the other hand, in a short CIC conductor, the length of which was approximately 1 m, there is no observation of the loop currents [22]. As a cause of non-occurrence of the loop currents in the CIC conductor, the strands are not

connected at the current terminal end, and thus no loop currents are measured. Therefore, the CIC conductor, the configuration of which is short and straight including current terminals, might generate loop currents even though the conductor length is not greater than or equal to several tens of meters. Using an EF joint sample composed of short straight CIC conductors with current terminals [5, 23], occurrences of loop currents were investigated.

5-2-1 Joint sample for the EF coil

Fig. 10 shows the configuration of the joint sample for the EF coils. This sample is composed of two lap joints of CIC conductors and two current terminals. Details of the sample are described in Refs. [5, 20]. To measure self-magnetic fields generated by a short straight CIC conductor with current terminals, four Hall sensors (HGCT-3020) were mounted around the CIC conductor as shown in Fig. 10. The position of the Hall sensors for the CIC conductor is illustrated in Fig. 11. Using the Hall sensors, the magnetic field in the y direction was measured.

5-2-2 Measurements of self-magnetic fields

Measurements of self-magnetic fields generated by the EF joint sample were conducted in the superconductor test facility [24]. Fig. 12 shows the measurement results of the magnetic field with the current wave of the joint sample. For the measurement, the joint sample was energized to 20 kA at a ramp rate of 100 A/s, and was maintained for 500 sec. Then the joint sample was degaussed at a ramp rate of 100 A/s. There was no external magnetic field for the joint sample. Fig. 13 shows the variation of the magnetic fields measured against time at each position after holding the joint sample current of 20 kA. Although the sample current was held, the magnetic fields were changed with several time constants. The time constants of the magnetic fields are listed in Table 4. The range of the time constants was 57-105 s, which means long time constants. The time constants indicated that loop currents occur in a CIC conductor, the length of which is approximately 1 m. Consequently, the CIC conductor length is not always related to long time constants. The occurrence of the loop current in the CIC conductor depends on the presence of either current terminals or current joints, rather than conductor length.

5-3. Evaluation of loop currents between strands through the current terminals

As described in Section 5-2, an occurrence of loop currents was observed in a short straight CIC

conductor with current terminals. In this section, the electrical characteristics of loop currents were investigated with an analytical model assuming loop currents with long time constants.

5-3-1 Analytical model

Superconducting strands in the short straight conductor of the joint sample for the EF coil were modeled with an electrical circuit. Fig. 14 illustrates the modeled electrical circuit composed of self and mutual inductances of two strands, and the resistances of two strands at current terminal and conductor joint. In this analysis, it is assumed that a loop current flows along strands through current terminals, and the current flow hampered by the twist of strands is not taken into account. To evaluate the self and mutual inductances of strands in the short straight conductor, the trajectories of strands were modeled. In modeling the strand trajectories, it is very difficult to reproduce the actual trajectories in the conductor of the JT-60SA EF coil. Therefore, in this analysis, the strand trajectories were simplified using a rotating radius of the strands' twist pitch shown in Fig. 15, which is comparable to the parameters of the multi-strand cable of the EF conductor. The specification of the model for the strand trajectories is listed in Table 5. Fig. 16 shows the schematic illustration of twisted strand trajectories of one petal in the model. The strand trajectory is made by connecting elements along the longitudinal direction.

To calculate self and mutual inductances of strands in the multi-strand cables, Neumann's formula was used [25] as follows:

$$L = \frac{\Delta s}{2\pi} \left[\frac{\mu_0}{4} + \mu_0 \left\{ \ln \left(\frac{2\Delta s}{r} \right) \right\} - 1 \right] \quad (1)$$

$$M = \frac{\mu_0}{4\pi} \iint \frac{\cos\theta}{l_{mn}} ds_m ds_n \quad (2)$$

where L is the self inductance of a strand, μ_0 is the vacuum permeability, Δs is the length of the element of a strand, r is the radius of a strand, M is the mutual inductance, l_{mn} is the distance between two different elements of each strand, and θ is the angle between different elements of each strand.

5-3-2 Analytical results

Mutual inductance between two strands in the analytical model was calculated. The layout of six petals in the analytical model is illustrated in Fig. 15. The fourth petal is furthestmost from the first petal. The correspondence between the strand number and the petal number is listed in

Table 6. The mutual inductance between one strand in the first petal and another strand in each petal is also shown in Table 6. The mutual inductance becomes smaller as the distance between one strand in the first petal and another strand becomes longer. The largest value of the mutual inductance is 1.39×10^{-6} H between strands in the first petal, and the smallest value is 8.29×10^{-7} H between the strand in the first petal and the furthest strand in the fourth petal.

From the equivalent circuit of two strands shown in Fig. 14, the time constant of the equivalent is given by

$$\tau = \frac{L_1 + L_2 - 2M}{R_{terminal} + R_{joint}} \quad (3)$$

where L_1 and L_2 are self inductances of a strand, M is mutual inductance between strands, $R_{terminal}$ is electrical resistance between two strands at the current terminal, and R_{joint} is electrical resistance between two strands at the conductor joint. Using Eq. 3, the electrical resistance between two strands at the current terminal was calculated assuming that R_{joint} is equal to $R_{terminal}$. This is because the current terminal and the conductor joint have the same conditions in that the multi-strand cable is compacted and soldered at the end of the short straight conductor. From the measurement results of the time constants of the short straight CIC conductor, the time constant is assumed to be 105 s. In this analysis, a time constant of a loop current in the equivalent circuit was investigated with two different mutual inductances between strands. Regarding the mutual inductance, 1.39 μ H and 0.83 μ H were used. 1.39 μ H indicates the mutual inductance between strands located in the same petal, and 0.83 μ H indicates the mutual inductance between a strand in the 1st petal and the furthest strand in the 4th petal. Self inductance of a strand is 1.62 μ H. As a result, in the equivalent circuit where a loop current with $\tau = 105$ s was generated, the electrical resistance between two strands located in the same petal was 25 $\mu\Omega$ at the current terminal. And the electrical resistance between two strands located in the two furthest petals was 167 $\mu\Omega$ at the current terminal. From the analytical results, loop currents can occur with the electrical resistance between strands ranging from several tens of $\mu\Omega$ to 100 and several tens of $\mu\Omega$ at current terminals in the CIC conductor, the length of which is approximately 1 m.

6. Conclusion

Self-magnetic fields of the JT-60SA CS1 module were measured in a cold test. As a result, the decay of self-magnetic fields was observed after the CS1 module was degaussed. The time constant of the decay ranged from 90 s to 269 s. The measurement results indicate that loop currents with long time constants, which are irregular coupling currents, occurred in the CS1 module due to coil energization.

Regarding a decay time constant of magnetic fields after coil excitation or demagnetization, the CS1 module was compared with the CS model coil. As a result, the time constant of the CS1 module was comparable with that of the CS model coil although the conductor length of the CS1 module is approximately ten times longer than that of the CS model coil. In the CS1 module, the butt joint connecting electrically each pancake coil will hamper loop currents with long time constants across the pancakes.

In order to investigate whether the loop currents can occur in a short straight CIC conductor the length of which was approximately 1 m, self-magnetic fields of the conductor were measured. In the short straight CIC conductor, a multi-strand cable was connected electrically at the conductor end. As a result, loop currents whose time constant ranged from 57 s to 105 s, occurred in the conductor. Loop currents with long time constants flow not only in large superconducting coil wound with CIC conductors but also in the short CIC conductor having current terminals. Therefore, the conductor length is not always related to loop currents with long time constants. The occurrence of loop currents having long time constants depends on the presence of current paths at the conductor end in the CIC conductor.

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Fig.1 Layout of the JT-60SA magnet system. The CS is composed of four modules (CS1, CS2, CS3, and CS4).

Fig.2 Photograph of the CS1 module.

Fig. 3 Configuration of the CS1 module. (a) Side view (b) Top view. P1, P2, P3, and P4 show the position of Hall sensors.

Fig. 4 CS1 module installed in the superconducting coil test facility.

Fig. 5 The position of each Hall sensor on the module. z direction in this figure corresponds to the axial direction of the CS1 module.

Fig. 6 Measurement results of self-magnetic field generated by the CS1 module.

Fig. 7 Self-magnetic fields at 140° after the coil degauss.

Fig. 8 Self-magnetic fields at 260° after the coil degauss.

Fig. 9 Schematic view of conductor lengths of the model coil and CS1 module.

Fig. 10 Joint sample for the EF coil.

Fig. 11 Position of the Hall sensors for the joint sample of the EF coil.

Fig. 12 Measurement results of self-magnetic field generated by the joint sample of the EF coil.

Fig. 13 Self-magnetic field of the short straight conductor in the joint sample during the sample current of 20 kA.

Fig. 14 Equivalent circuit of two superconducting strands in the short straight CIC conductor with conductor terminal and joint.

Fig. 15 Cabling configuration of the model for inductance calculation.
 R_{1st} , R_{2nd} , R_{3rd} , and R_{4th} indicate the rotation radii of twist pitch at 1st stage, 2nd stage, 3rd stage, and 4th stage, respectively. The cable is composed of six petals.

Fig.16 Schematic illustration of twisted strand trajectories of one petal in the model. The trajectory of a strand is made by connecting elements along the longitudinal direction.

Configuration	Six OP* + one QP**
Number of layers	52
Number of turns	549
Inner diameter [m]	1.3
Outer diameter [m]	2
Height of coil winding [m]	1.6
Weight [ton]	18

OP* and QP** are abbreviations of octa-pancake coil and quad-pancake coil, respectively.

Table 2 Specifications of the CS conductor.

Strand diameter [mm]	0.82
Strand surface	Cr plating
Number of Nb ₃ Sn strands	216
Number of Cu wires	108
Cabling pattern	(2 + <u>1Cu</u>) × 3 × 6 × 6
Twist pitch [mm]	45/85/125/160
Sub-wrapping	w/o
Void fraction [%]	34
Jacket outer size [mm×mm]	27.9×27.9
Cabling diameter [mm]	21.0
Central spiral (id/od) [mm]	7/9

Table 3 Time constants of self-magnetic fields at each position in the CS module coil after the CS module current reached to 0 A.

Hall sensor	Time constant	Hall sensor	Time constant
B4	124 s	B14	90 s
B5	176 s	B16	269 s
B6	100 s	B18	121 s
B7	197 s	B19	202 s
B8	239 s	B20	204 s
B9	171 s	B21	216 s
B10	165 s	B22	178 s
B11	142 s	B23	142 s
B12	268 s	B25	186 s
B13	184 s	B26	—

Table 4 Time constants of self-magnetic fields at each position in the EF joint sample during the sample current of 20 kA.

Hall sensor	Time constant
HS-24	80 s
HS-25	71 s
HS-26	57 s
HS-27	105 s

Table 5 Specification of the model for inductance calculation.

Strand diameter [mm]	0.83
Number of strands	450
Cabling pattern	$3 \times 5 \times 5 \times 6$
Twist pitch at each stage [mm]	45 (1st) / 85 (2nd) / 125 (3rd) / 160 (4th)
Rotating radius of twist pitch at each stage [mm]	1 (1st) / 2 (2nd) / 4 (3rd) / 8 (4th)
Strand length in the z direction [mm]	1065

Table 6 Mutual inductance and correspondence between petal and strand number for the analytical model.

Petal number	Strand number	Mutual inductance for a strand in 1st petal
1st	1 – 75	$9.98 \times 10^{-7} - 1.39 \times 10^{-6}$
2nd	76 – 150	$9.43 \times 10^{-7} - 1.00 \times 10^{-6}$
3rd	151 – 225	$8.64 \times 10^{-7} - 8.69 \times 10^{-6}$
4th	226 – 300	$8.29 \times 10^{-7} - 8.33 \times 10^{-7}$
5th	301 – 375	$8.66 \times 10^{-7} - 8.68 \times 10^{-7}$
6th	376 – 450	$9.55 \times 10^{-7} - 1.01 \times 10^{-6}$