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Results of All ITER TF Full-Size Joint Sample Tests in Japan

Hideki Kajitani, Shinsaku Imagawa, Tetsuhiro Obana, Suguru Takada, Shinji Hamaguchi, Hirotaka Chikaraishi, Mio Nakamoto, Minoru Yamane, Kazumi Yoshizawa, Yasuhiro Uno, Kunihiro Matsui, Norikiyo Koizumi and Masataka Nakahira

***Abstract*— Nine toroidal field (TF) coils have been developed in Japan for the international thermonuclear experimental reactor (ITER). The joint resistance of TF coil should satisfy the requirement of smaller than 3 nano-ohm at 2 T of external magnetic field and 68 kA of transport current. Full-size joint sample (FSJS) tests were performed for joint development and for TF coil manufacture, as part of the process control. 11 FSJS tests are conducted in total. FSJS tests were conducted with assistance from a test faculty in the National Institute for Fusion Science as reported in a previous paper. All FSJS tests successfully satisfied the requirement of resistance less than 3 nΩ at 2 T. Additionally, the TF coil joints are subjected to cyclic electromagnetic force and warm-up/cool-down during the ITER operation. The authors investigated the joint performance for the abovementioned influence. The results showed no degradation in the joint resistance. Thus, the TF joint developed in Japan was qualified successfully.**

***Index Terms*— ITER TF coil, TF joint, joint resistance**

I. Introduction

NINE toroidal field (TF) coils have been developed in Japan for the international thermonuclear experimental reactor (ITER). The TF coil consists of seven double-pancakes (DPs). DPs are Nb_3Sn cable-in-conduit conductors wound to a D-shape and inserted into groove of a radial-plate with conductor insulation [1]. The completed seven DPs are stacked, ground-insulated and then, each DP is electrically connected to the adjacent DPs through electrical joints at the both ends of the conductor. Thus, all the DPs are connected electrically [2]. ITER TF coil joint is a box-type joint, and its details are explained in the following sections.

For each TF coil, it is necessary to achieve a sufficiently low joint resistance of less than 3 nΩ for each of the 6 inter-DP joints and 4 nΩ for each of the 2 terminal busbar joints with an external field of 2 T and a transport current of 68 kA. For real TF joint, the soundness of the joint resistance was evaluated at room temperature according to previous studies [3][4]. In addition to these evaluations, full-size joint sample (FSJS) tests were also performed as a process control in the TF coil fabrication. The details of the FSJS test are described in [5]. Thus, the TF coil joint is sufficiently qualified. In this study, FSJS tests are focused upon.

Since there are two manufacturers of TF coils in Japan, the FSJS test was performed by each manufacturer as a qualification test in the development phase. In addition, FSJS tests were performed for every coil in the TF coil production. The total number of FSJS tests is therefore eleven, including two qualification tests and nine process controls. The first FSJS test was performed in August 2013. The final FSJS test was then performed in March 2020. All FSJS tests achieved sufficiently low joint resistance. The results are reported in this paper.

In addition, the TF coil joints experience cyclic of electromagnetic (EM) force and warm up/cool down (WU/CD) during the ITER operation. Therefore, the authors investigated the joint performance for such an influence in some FSJS tests. These results are also presented in this paper.

II. FSJS test

All FSJS tests were performed at a large-scale conductor test facility at the National Institute for Fusion Science (NIFS) located in Japan. This test facility was suitable for the FSJS test because it has a 75-kA power supply, 100-kA current lead, and 9-T magnet systems [6].

The major parameters and overview of FSJS are shown in Table I and Fig. 1. FSJS consists of two short straight TF conductors. Each conductor, which consists of 900 Nb_3Sn and 522 copper strands, has two joint boxes at both ends, named as the lower and upper joints. Two lower joints (tested part), which is the full-size joint of the TF coil, are electrically connected by soldering, while each upper joint (terminal) is electrically connected with the current lead of the test facility through a copper busbar.

Since two types of conductors, Bronze-Route (BR) and Internal-Tin (IT) Nb_3Sn conductors, are used in Japanese nine TF coils, FSJS using both conductor types are tested. The FSJS number and conductor type are summarized in Table II. Five FSJSs were fabricated from BR (FSJS no. TF01-05), while six FSJSs from IT (FSJS no. TF06-11).

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H. Kajitani is with National Institutes for Quantum and Radiological Science and Technology (QST). 801-1, Mukouyama, Naka-shi, Ibaraki, 311-0193, Japan (e-mail: kajitani.hideki@qst.go.jp)

TABLE I
MAJOR PARAMETERS OF ITER TF JOINT

Conductor	
Cabling layout	(3[a]×3×5×5+core[b])×6
Strand diameter	0.82 mm
Twist pitch	81/140/186/298/420 mm
Jacket material	316LN
Inner jacket diameter	39.7 mm
Outer jacket diameter	43.7 mm
Void fraction	33%
Joint	
Overall joint length	675 mm
Cable compaction length in joint	440 mm
Void fraction	25%
Joint box material(SS part)	316LN
Joint box material(Copper sole)	C1020
RRR of copper sole	>300

[a]Two of the three strands are Nb_3Sn and the third one is Cu
[b]Core consists of 3×4 Cu wires.

TABLE II
FSJS NUMBER AND CONDUCTOR TYPE

FSJS no.	Conductor type
TF01	Bronze-Route (BR) Nb_3Sn strand
TF02	
TF03	
TF04	
TF05	
TF06	Internal-Tin (IT) Nb_3Sn strand
TF07	
TF08	
TF09	
TF10	
TF11	

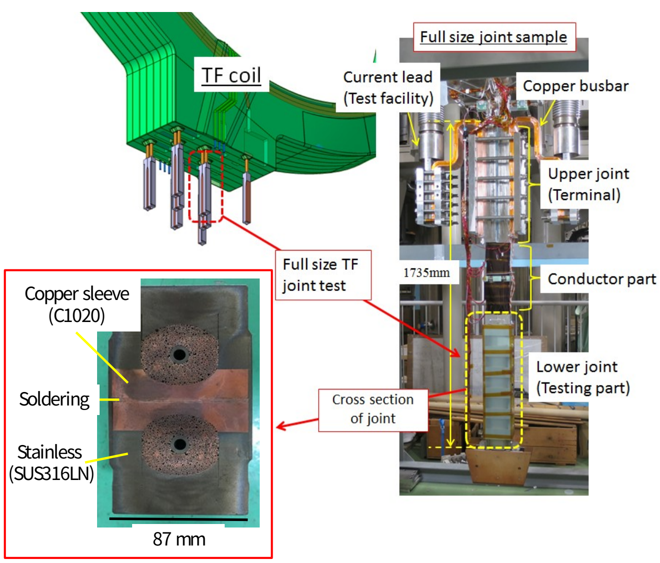

Fig. 1. Overview of FSJS. The test was carried out by using NIFS test facility

TABLE III
RELATION BETWEEN MAXIMUM AND MINIMUM EXTERNAL MAGNETIC FIELD

Maximum [T]	Minimum [T]	Average [T]
4.8	3.0	3.9
3.7	2.3	3.0
2.4	1.5	2.0

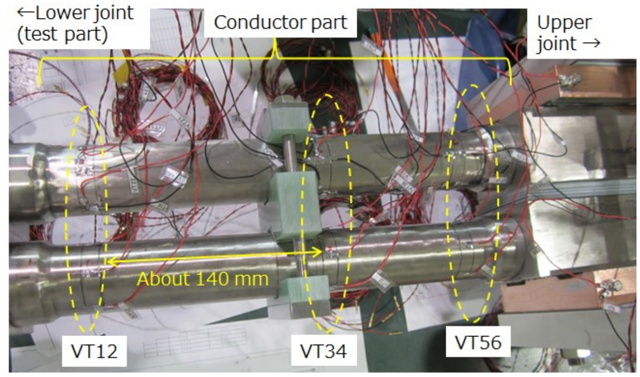

Fig. 2. Voltage taps (VTs) attached to the conductor part of FSJS. They are installed on three positions of conductor part along with the axial di-rection, named as VT12, VT34 and VT56. Each VT12, VT34 and VT56 consists of six pairs of voltage taps in a circumferential direction. Each distance between VTs is about 140 mm.

III. TEST METHOD

A brief explanation of the FSJS test method is provided in this section based on the details shown in [4]. An FSJS fabricated by TF coil manufacturers is installed in the NIFS test facility, and copper busbars attached to the upper joint are connected to the current leads of the test facility. The FSJS itself is cooled with supercritical helium from the bottom. The temperature of FSJS is controlled with tape heaters that are attached to the inlet cooling pipe. A pair of voltage taps (VTs) is set across the lower joint to evaluate the joint resistance. They are installed at three positions of the conductor part along the axial direction, namely, VT12, VT34, and VT56, as shown in Fig. 2. VT12, VT34, and VT56 consist of six pairs of VTs in a circumferential direction (called star taps). Each distance between VTs is about 140 mm.

The lower joint is set at the center of the test facility coil, which applies an external magnetic field to it. With the feature of the coil, the external magnetic field varies along the axis of the joint. The maximum field is generated at the center of the coil, and it gradually decreases along the joint. Thus, the external magnetic field applied to the joint is summarized in Table III. Since the authors should evaluate joint resistance more than 2 T of external magnetic field based on the ITER operation, 3.7 T of the maximum field (i.e., 2.3 T of minimum field) is selected to judge the soundness of the joint resistance. During application of an external magnetic field, the transport current is ramped with the plateau of 15, 30, 45, 60 and 68 kA. To eliminate an inductive effect, the current was hold in 3 min at each plateau. Voltages on sufficiently plateau at each current ramping are utilized. Then, the joint resistance is evaluated as a slope of these voltages and currents.

IV. MEASUREMENT RESULT

The measurement results of the FSJSs listed in TABLE II are reported in this section. The joint resistance was evaluated by the averaged voltage of the star taps. The following subsections present the influences of various parameters, such as the direction of the external magnetic field, conductor type, EM force cycles, and WU/CD, on joint resistance. The purpose of categorization of external magnetic field direction and conductor types is to assess intrinsic characteristic of the joint. On the other hand, the purpose of categorization of EM force cycles and WU/CD is to assess influence of ITER operation on the joint resistance as mentioned above.

A. *Influence of external magnetic field direction (FSJS no. TF01 and TF06)*

FSJS no. TF01 and TF06 were the first tested ones for each conductor type. These were tested with various external magnetic fields to determine the influence of the field direction, as shown in Fig. 3. Negative and positive signs of the field indicate the direction of the external magnetic field. In negative/ positive fields, the lower joint is compressed/expanded due to EM force. The results of joint resistance are shown in Fig. 4 for TF01 and Fig. 5 for TF06 as a function of the maximum external magnetic field. The joint resistances were evaluated in three VTs, as shown in Fig. 2. VT12, VT34, and VT56 are described as round, triangle, and rectangle points, respectively. The reason for the difference between these VTs is described in [4]. All of the joint resistances could be below 3 nΩ in both Figs. 4 and 5.

According to Fig. 4, the joint resistances in the positive external field appear to be slightly higher than those in the negative field, while there was almost no difference between them in Fig. 5. A possible explanation for the difference in the positive and negative shown in Fig. 4 may be magnetic resistance of the joint due to the self-magnetic field shown in Fig. 3. However, such an influence is sufficiently small for joint resistance evaluation. Therefore, further FSJS tests were performed only in positive external magnetic field.

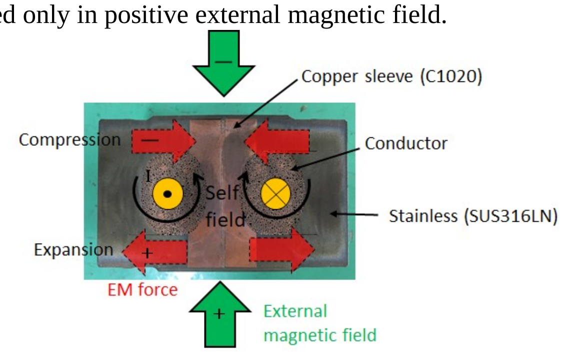

Fig. 3. Direction of external magnetic field on the joint cross section. Negative and positive signs of the field indicate the direction of the external magnetic field. In negative/positive fields, the lower joint is compressed/expanded due to EM force.

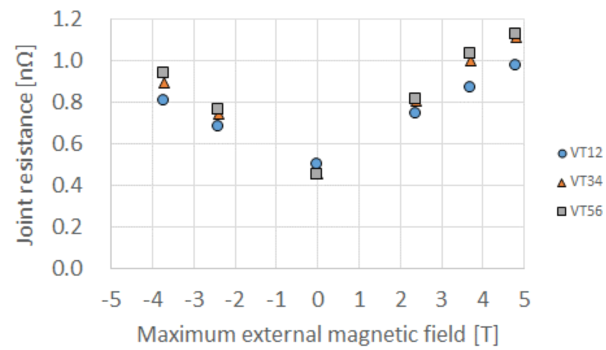

Fig. 4. Joint resistances of full-size joint sample (FSJS) no. TF01 as a function of maximum external magnetic field.

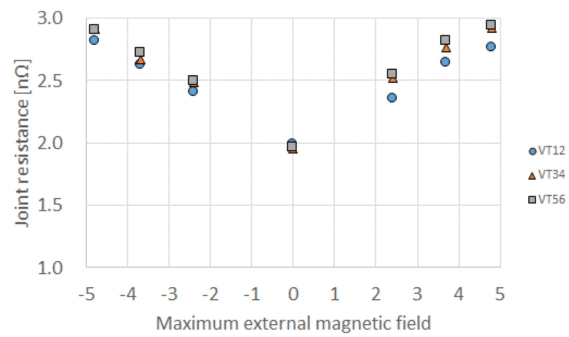

Fig. 5. Joint resistances of FSJS no. TF06 as a function of maximum external magnetic field.

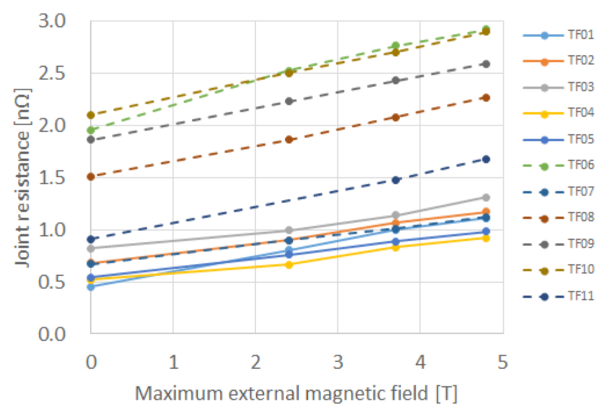

Fig. 6. Joint resistances of FSJS no. TF01-11 as a function of maximum external magnetic field. BR of TF01–05 and IT of TF06–11 is shown in solid and dotted lines, respectively.

B. *Influence of conductor type (FSJS no. TF01-TF11)*

All joint resistances from FSJS no. TF01 to TF11 are summarized in Fig. 6 as a function of the maximum external magnetic field, using the same style as shown in Fig. 4, while only the results of VT34 are shown in Fig.6 to clarify the discussion. To see the influence of conductor type, the BR of TF01-05 and IT of TF06-11 are shown in solid and dotted lines, respectively. According to Fig. 6, as a whole trend, the joint resistances of the IT conductor type (TF06-11) seem to be higher than that of BR conductor type (TF01-05). One of the possible explanation is increase of copper resistance due to contamination of Copper by Tin during heat treatment. More detailed study should be necessary to confirm the reason of scattering in Fig.6. Anyway, the authors can conclude that sufficiently low joint resistances could be achieved in both types of conductor.

C. Influence of EM cycles (FSJS nos. TF02, TF04 and TF09)

The joint experiences EM force during ITER operation. Therefore, EM cycle tests were performed for FSJS nos. TF02, TF04 and TF09. Note that 500 EM cycles were applied on TF02 and TF09 while 1000 EM cycles were performed on TF04. EM cycles were performed by charging 33.6 kA of transport current and 7.5 T of maximum external magnetic field to simulate the same EM force of ITER operation (i.e., EM cycle condition: 33.6 kA×7.5 T ≃ ITER operation: 68 kA×3.7 T). Thus, the current cycles are shorter at 33.6 kA than at 68 kA of transport

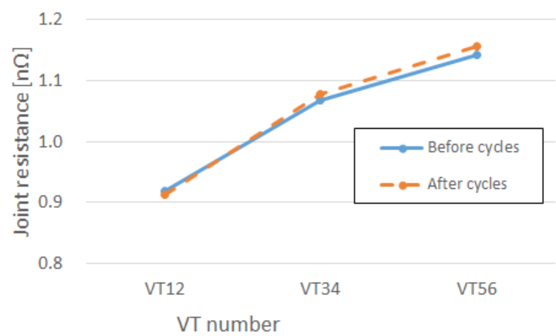

Fig. 7. Joint resistances of FSJS no. TF02 before and after the electromagnetic (EM) cycles. 500 EM cycles were applied. Solid and dotted lines represent before and after EM cycles, respectively.

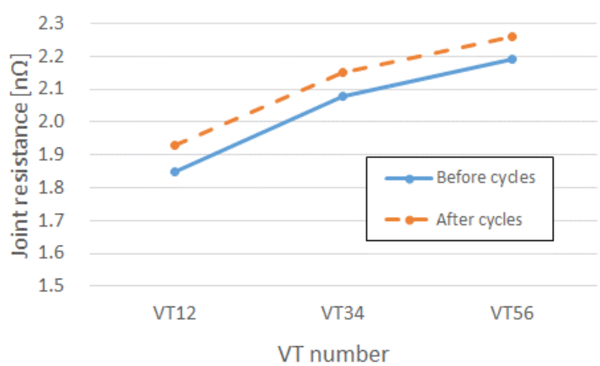

Fig. 8. Joint resistances of FSJS no. TF09 before and after electromagnetic (EM) cycles. 500 EM cycles were applied. Solid and dotted lines represent before and after EM cycles, respectively.

current. Before and after the EM cycles, the joint resistance was evaluated under the condition that the transport current and maximum external field were 68 kA and 3.7 T, respectively. The results of the joint resistance before and after the EM cycles are shown in Fig. 7 for TF02 and Fig. 8 for TF09 as a function of VT number. The result of TF04 is described associated with a WU/CD result in the next section. According to these results, joint resistances were slightly increased by EM cycles due to probable cable movement, which leads to change of contact resistance between cable and copper sole in the joint. However, it was revealed that sufficiently low joint resistance could be kept even after EM cycles in both conductor types.

D. Influence of WU/CD (FSJS no. TF04)

The joint also experiences a thermal cycle of WU/CD during ITER operation. Therefore, WU/CD was applied to FSJS no. TF04, in addition to EM force cycles. The TF04 test procedure is as follows:

1. Measurement of initial joint resistance was performed,
2. 1000 EM cycles were applied. Then, the joint resistance was measured (same procedure as previous section),
3. WU/CD was applied from approximately 4 K to room temperature, and
4. Cool down was performed again. Then the joint resistance was measured.

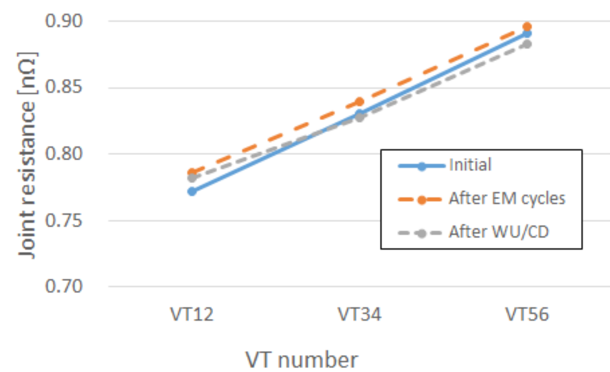

Fig. 9. Joint resistances of FSJS no. TF04. Solid, long dotted, and short dotted line show initial, after electromagnetic (EM) cycles, and after warm up/cool down, respectively. 1000 EM cycles were applied.

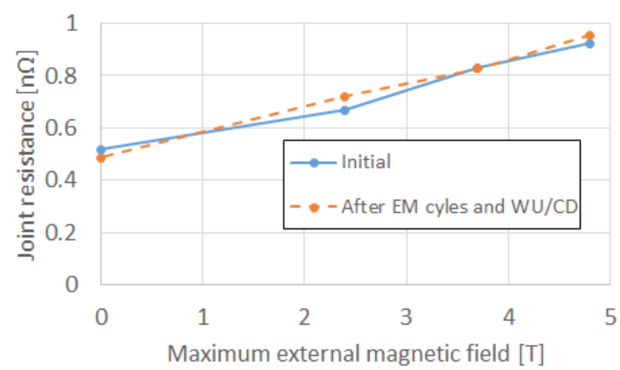

Fig. 10. Joint resistances of FSJS no. TF04 as a function of maximum external magnetic field. Solid and dotted line show initial and after electromagnetic (EM) cycles and warm up/cool down, respectively. 1000 EM cycles were applied.

The results of joint resistances on the test campaign above are shown in Fig. 9 as a function of VT number. Each joint resistance in Fig. 9 was evaluated on the condition that the transport current and maximum external magnetic field were 68 kA and 3.7 T, respectively. According to Fig. 9, there is almost no change in joint resistance among the test campaign above. In addition, joint resistances were also evaluated as a function of the maximum external magnetic field shown in Fig. 10 using the same style as that shown in Fig. 6. In Fig. 10, the initial joint resistances (No. 1 in the procedure above) and joint resistances after WU/CD (No. 4 in the procedure above) are shown. From these results, the authors can say that there is pragmatically no degradation of joint resistance even if EM cycles and WU/CD were applied.

V. Conclusion

FSJS tests were performed from 2013 to 2020. As a result, all of them could show sufficiently low joint resistance. In addition, influences of external magnetic field direction, conductor type, EM force cycles, and WU/CD, on joint resistance were also studied. Therefore, there was pragmatically no degradation in joint resistance. This means that the ITER TF joint will be able to survive in ITER operation without any significant degradation. According to these results, it can be deduced that all TF coil joint could be qualified in Japan.

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