Evaluation of ITER TF Coil Joint Performance

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***Abstract*—To evaluate the ITER TF joint performance, the joint test sample, which consists of two short TF conductors and has full size joint, shall be tested using NIFS test facility under the condition of current of 68 kA and external field of 2 T. For high accuracy, the issue of voltage difference between cable and jacket had been anticipated in the evaluation of joint resistance. If a voltage difference exist between them, it is difficult to measure real joint resistance using voltage taps on the jacket. Therefore, the author first calculated the position where voltage of cable and jacket become equipotential and then decided the voltage tap position where the influence of voltage drop could be avoided. Thus, a high accuracy measurement of joint resistance could be achieved and the joint resistance was accurately evaluated as around 1 nΩ, which is well below the ITER requirement of 3 nΩ.**

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

I. Introduction

THE performance of ITER TF coil proto joint shall be measured to confirm that the joint performance satisfies the requirement of below 3 nΩ under the condition of current of 68 kA and external magnetic field of 2 T. The test is performed using large scale conductor test facility at National Institute for Fusion Science (NIFS) located in Japan. This test facility is suitable for the test because it has 75 kA power supply, 100 kA current leads and 9 T magnet systems [1]. However, in measurement of voltage in the test, measured voltage may have a mix of cable voltage due to joint resistance and voltage drop between cable and jacket. The author therefore shall distinguish them and avoid the influence of voltage drop between them for high accuracy evaluation. Indeed, these issue arose on CS model coil butt joint sample and had been reported by Koizumi *et al.* [2].

Thus, the calculation to anticipate the position where cable and jacket become equipotential was first performed using a circuit model and then the position of voltage taps on the jacket was decided based on the result of calculation. In this paper, the details of the developed model and its calculation result are described. Then, the evaluation of joint resistance is shown.

II. Major Parameters of Sample

Full size joint sample consists of two short straight TF conductors, L-leg and R-leg conductors like a SULTAN sample [3]. Each conductor, which consists of 900 Nb_3Sn and 522 copper strands, has two joint boxes at both ends, named as lower and upper joint. Two lower joints (tested part) ,which is full size joint of TF coil, are electrically connected by soldering while each upper joint (terminal) is electrically connected to the current leads of the test facility through a copper bus-bar. The cable is compacted from the void fraction of 33 % to 25 % at the lower joint on 440 mm although the total length of the joint box is 675 mm, which includes the transition region of cable compaction. The major parameter and a schema of the sample are shown in Table I and Fig. 1.

TABLE I
MAJOR PARAMETERS OF SAMPLE

Conductor	
Cabling layout	$(3^{1)}\times3\times5\times5+\text{core}^{2)})\times6$
Strand diameter	0.82 mm
Twist pitch	81/140/186/298/420 mm
Jacket material	316LN
Jacket inner diameter	39.7 mm
Jacket outer diameter	43.7 mm
Void fraction	33 %
Joint	
Over all of joint length(Testing part)	675 mm
Cable compaction length in joint	440 mm
Void fraction	25 %
Joint box material(SUS part)	316LN
Joint box material(Copper part)	C1020

*1) Two of the three strands are Nb_3Sn and the third one is Cu
*2) Core consists of 3×4 Cu wires

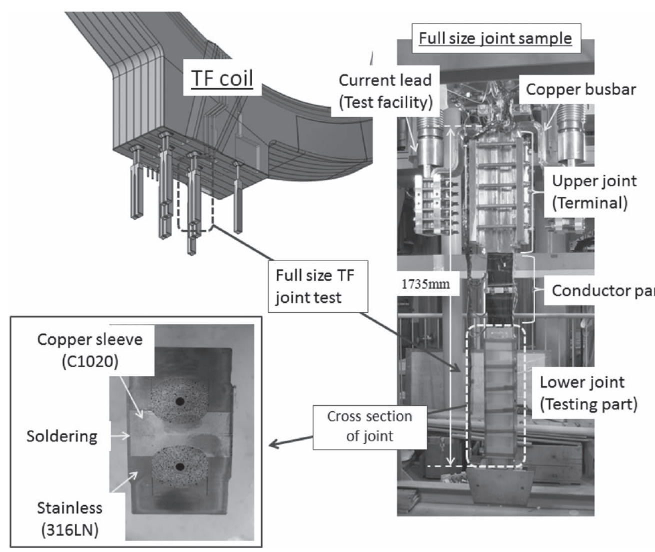

Fig. 1. Full size joint sample.

III. Sensor Location

If voltage taps (VTs) could be directly attached to the cable, the joint resistance could be easily measured as the resistance

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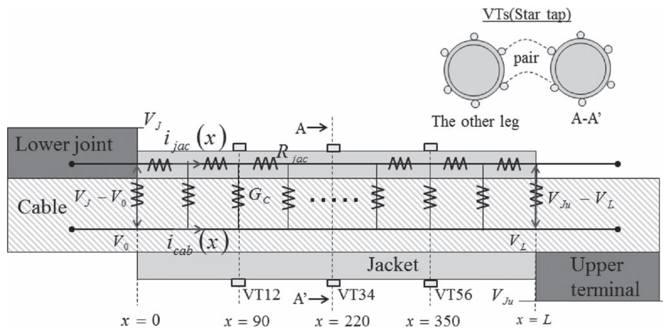

Fig. 2. Distributed circuit model of cable and jacket for one leg.

of cable is basically zero. However, it is impossible and the voltage shall be measured via the jacket. Because the voltage difference between cable and jacket exists due to electrical resistance between them, the VTs should be set on the region where the voltage of the cable and jacket become equipotential to avoid the influence of voltage drop between them.

The author applied the distributed circuit model between cable and jacket to calculate the equipotential region. The calculation model is shown in Fig. 2. Note that the resistance of cable is set to be zero and current flows from lower joint to upper terminal in Fig. 2. In addition, because the sample could be assumed as symmetric for L and R leg, the circuit model is applied for only one leg.

The governing equation of the distributed circuit model of Fig. 2 is as following:

$$\frac{d^2 i_{cab}}{dx^2} - G_C R_{jac} i_{cab} = -G_C R_{jac} I_t \tag{1}$$

where i_{jac} [A] and i_{cab} [A] denote the current of jacket and cable, respectively, G_C [S/m] the conductance between cable and jacket per unit length, R_{jac} [Ω/m] the resistance of jacket per unit length, I_t [A] the total sample current and x [m] the coordinate of sample longitudinal direction. To solve of Eq. (1) for i_{cab}

$$i_{cab}(x) = C_1 \exp\left(\frac{x}{\lambda}\right) + C_2 \exp\left(-\frac{x}{\lambda}\right) + I_t \tag{2}$$

$$\lambda = \frac{1}{\sqrt{G_C R_{jac}}} \tag{3}$$

where C_1 and C_2 are integral constant.

The λ means the penetration length to be equipotential from the lower joint [4]. If the distance of VT position from the lower joint is longer than the λ, the VT could avoid the influence of voltage difference between the cable and jacket because it is equipotential region. In contrast, if the distance is shorter than the λ, the VT could not do because it is not equipotential region. Thus, VT should be attached in the position where the distance from the lower joint is longer than the λ. In this section, because what the author intends to know is equipotential region, only Eq. (3) shall be calculated.

In calculation of Eq. (3), R_{jac} is assumed to be 8×10^{-5} Ω/m from the stainless resistivity of 2×10^{-8} Ωm and the configuration of jacket. G_C may be assumed to be around 10^6 S/m from data of [2]. However, the value of G_C is difficult to set because it depends on the transverse pressure due to electromagnetic force. Therefore, G_C is given the range from 10^5 to10^7 S/m in this calculation.

The calculation result of λ is 350 mm and 35 mm in G_C of 10^5 S/m and 10^7 S/m each other. Thus, λ may be 35 mm–350 mm. However, due to limitation of sample space of the test facility, the total length of sample should be less than 1735 mm while the length of lower joint is fixed at 675 mm to be same as ITER TF joint. Therefore, the remaining 1060 mm is divided between conductor and upper terminal part. Because the λ shall be considered for both upper terminal and lower joint, the length of conductor part is at least needed as 700 mm if the λ is 350 mm, which means that the length of upper terminal become 360 mm. It is too short. Current imbalance may be established in the cable due to the poor number of cable contact with copper sleeve in upper terminal. The additional consideration thus shall be applied for the λ to narrow down the range of it.

In the case of CS model coil butt joint sample reported by [2], the λ was about 150 mm from the measured voltage distribution. The jacket thickness of ITER TF joint sample is thinner than one of CS butt joint sample. In addition, the void fraction of ITER TF joint sample is smaller than one of CS butt joint sample. R_{jac} and G_C are thus considered to be larger in case of ITER TF joint sample compared with CS butt joint sample. Therefore, the λ of ITER TF joint sample could be at least shorter than 150 mm of CS butt joint sample. The author thus could assume the λ as 35 mm–150 mm.

From the evaluation of the λ as mentioned above, the VT was decided to be set in 220 mm from the lower joint with some λ margin to be sufficiently equipotential region. Then the length of conductor part is 440 mm, which means that the length of upper joint could be 620 mm almost same as lower joint.

In addition, VTs were also attached at 90 mm and 350 mm from the lower joint each other to check the voltage distribution along the axis of sample. Moreover, so-called star taps, which consist of VTs attached to the jacket at an interval of 60 degree in a circumferential direction, were set at each VT position to check the voltage distribution also in circumferential direction due to current imbalance among strands [5].

IV. Experimental Method

The joint sample is installed into NIFS test facility and copper bus-bars, which are attached upper terminal, are connected with the current leads of test facility. The sample is inserted in a stainless steel case that prevents the sample from being immersed with liquid helium, which cools 9 T split coils, to change the sample temperature. The sample itself is cooled with pressurized helium from the bottom of sample at helium flaw rate of 3 g/s and inlet pressure of 0.5 MPa. The temperature of the sample is controlled with tape heaters that are attached on the inlet cooling pipe. The temperature of sample is monitored with thermo sensors attached on the jacket.

The lower joint is set at the center of the split coil. With the feature of NIFS test facility, the external field from the split coil varies along the axis of the joint. A sample current is supplied from the upper terminal via copper bus-bar and flows through the lower joint. The sample current is ramped with the plateau

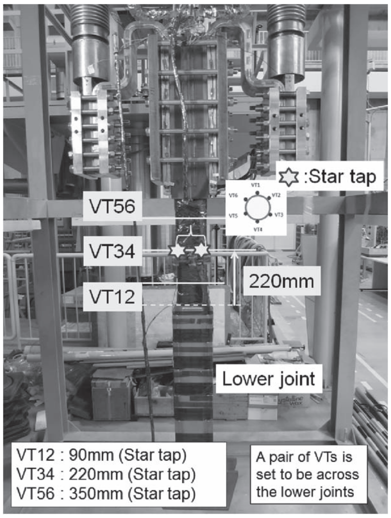

Fig. 3. VT locations of the sample.

of 0 kA, 15 kA, 30 kA, 45 kA, 60 kA and 68 kA. The ramping rates are 150 A/sec in charging and 600 A/sec in discharging. To eliminate effect of induced current by ramping, the current is hold in 3 min at each plateau. During charging the sample, the external field and supplied coolant temperature are set to be constants. A pair of VTs is set to be across the lower joints and named as VT12 (90 mm), VT34 (220 mm) and VT56 (350 mm) from near side of the lower joint and these VTs are used to evaluate joint resistance. Each VT12, VT34 and VT56 consists of six pairs of VTs in a circumferential direction as shown in Figs. 2 and 3. Thus, the voltages due to joint resistance are measured by eighteen pairs of VTs. All of signals from VTs are collected at intervals of 10 ms and voltages in last 10 s at each current holding (i.e. each current step) are utilized to eliminate effect of induced voltage for evaluation of joint resistance.

V. Experimental Result

The joint resistances were evaluated as a slope of linear approximation of the measured voltages (V) and currents (I) shown in Fig. 4. Some test campaigns were performed varying external field and supplied coolant temperature and the results of joint resistance are shown in Fig. 5. The longitudinal axis of Fig. 5 denotes the maximum external field which is generated by split coil. Because external field changes in the axial direction of the sample as mentioned above, the correlation of maximum and minimum field, which are applied to lower joint, is indicated as Table II. In addition, negative and positive signs of the maximum external field indicate the direction of external field. In negative/positive, lower joint is compressed /expanded due to electromagnetic force. Note that the joint resistances shown in Fig. 5 were obtained using average value of voltage in each star taps because a voltage distribution of circumferential direction among star taps was relatively small compared with the voltage level due to joint resistance. In Fig. 5, the joint resistances increased with increasing external field. This is due to the effect of increasing magnetic resistance of copper. On the other hand, the influence of the increasing temperature was relatively small.

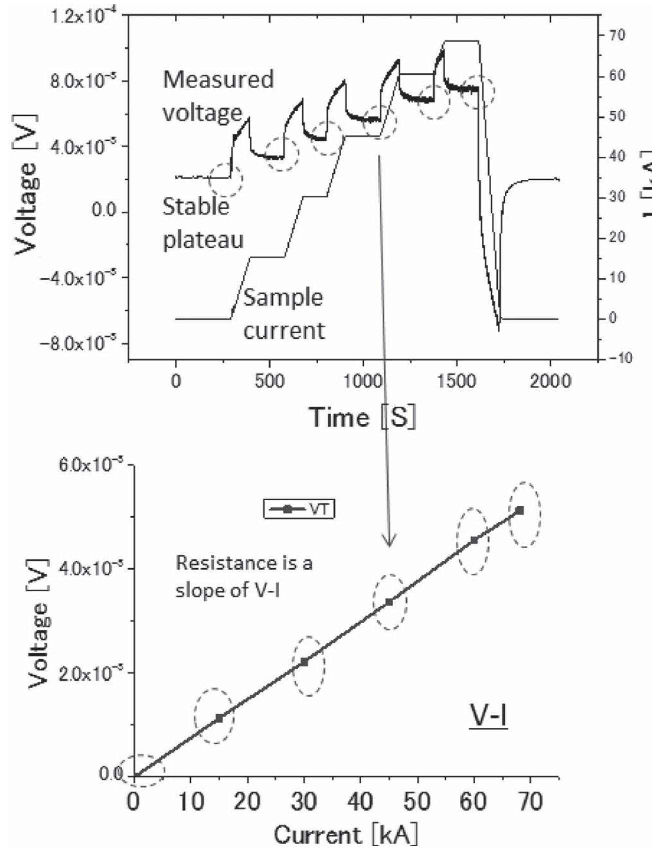

Fig. 4. Calculation procedure of joint resistance.

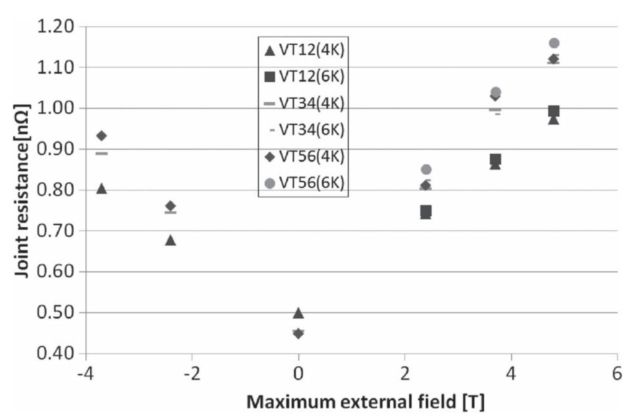

Fig. 5. Results of joint resistance as a function of maximum external field.

TABLE II
Relation Between Maximum and Minimum External Field

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

VI. Evaluation of Joint Resistance

All of joint resistance could be achieved around 1 nΩ. Thus, full size joint performance was qualified. However, the joint resistance increased with the increasing distance from the lower joint as shown in Fig. 6. Note that the values of joint resistance in Fig. 6 are same as one in Fig. 5.

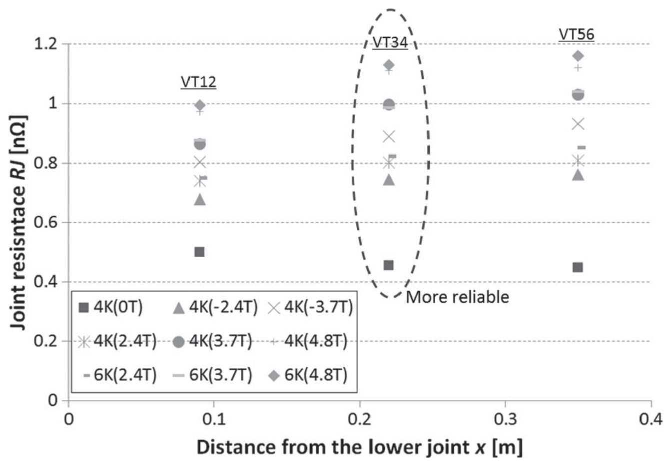

Fig. 6. Distribution of measured joint resistance along the axes of sample.

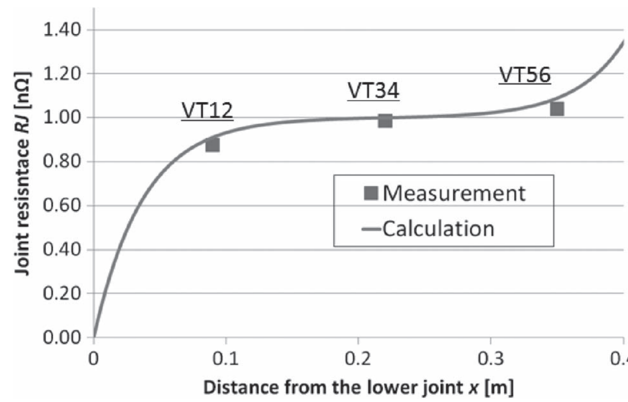

Fig. 7. Fitting results of calculated and measured joint resistance.

One explanation for this increase is remaining penetrated current in the jacket. If the penetrated current doesn't exist, which means that it is sufficiently equipotential between cable and jacket, the joint resistances shall be constant. On the other hand, if penetrated current exists, which means that voltage difference exists between them, the joint resistance shall be different at each VT position depending on the degree of voltage difference. Then, the joint resistance increases along the conductor length due to accumulation of the voltage difference. The other explanation is complicated current distribution among strands in the joint and it has been studied by many scientists [6], [7].

In ITER TF joint test, because the λ is 35 mm–150 mm as mentioned above, VT34, which were set in 220 mm from the lower joint, could be considered as more reliable for evaluation of joint resistance.

To confirm this consideration, the real G_C was estimated by fitting joint resistance calculated from the distributed circuit model shown in Fig. 2 to measured one. The fitting was carried by parameterizing G_c for the measured value in 4 K of temperature and 3.7 T of maximum external field.

Note that in the calculation, V_J in Fig. 2 was set to be zero as reference potential. In addition, resistance of copper sleeve of the joint was assumed to be negligible compared with contact resistance among strands and between copper sleeve and strand in the joint. Thus, the voltage of jacket is zero at $x = 0$ and then the joint resistance at $x = 0$ become zero in Fig. 7.

The fitting result is shown in Fig. 7. The calculation is good fit to the measured and the G_C is estimated as 9×10^6 S/m. When the λ is recalculated using this value, the λ become 37 mm. This is sufficiently enough to make the position of VT34 equipotential. Thus, it could be concluded that the joint resistance evaluated using VT34 is definitely pure one.

VII. Conclusion

The full size joint test shall be performed using large scale conductor test facility of NIFS located in Gifu Prefecture, Japan. However, in terms of limitation of sample space of the test facility, the length of sample should be limited. The influence of voltage difference between cable and jacket had been concerned in the evaluation of joint resistance. To achieve high accuracy, the author preliminarily calculated the region where cable and jacket become equipotential using distributed circuit model and then set VTs there. The test was performed under the variation of external field and sample temperature. The result showed that all of joint resistances could be achieved as around 1 nΩ, which is sufficiently below 3 nΩ of ITER requirement. Thus, full size joint performance was qualified. In addition, to more accurately evaluate the joint resistance, the author found the real G_C by fitting calculated joint resistance to measured one and the value could be obtained as 9×10^6 S/m. Then real λ was clarified as 37 mm. This indicates that the VT34 position was sufficiently equipotential region. Thus, it could be concluded that the joint resistance evaluated using VT34 is definitely pure one.

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