Dependence of Joint Resistance on Current for ITER-TF Joint Samples

S. Imagawa[1)], H. Kajitani[2)], T. Obana[1)], S. Takada[1)], S. Hamaguchi[1)], H. Chikaraishi[1)], K. Takahata[1)], K. Matsui[2)], and N. Koizumi[2)], ([1)]NINS NIFS, [2)]QST)

Abstract

Joint resistances of ten short samples have been measured until 2019 summer as a qualification test for ITER Toroidal Field (TF) coils. The joint sample consists of two short TF conductors with the length of 1.535 m, and each conductor has two joint boxes at both ends. The lower joint is a testing part that is full size joint of the TF coil. The upper joint is connected to 100 kA current leads of a conductor test facility. Voltage taps are attached at three positions in the original conductor part of the length of 0.3 m between the two joint boxes. Hall probes are attached on the lower joint box at around the center of the external field coils to measure the shielding current.

The joint resistance of the lower joint is estimated from the increase of the average voltage drop among the six voltage taps against the currents. In all the samples, the difference among the voltages of the six taps is enlarged to the range of 0.01 mV and saturated at less than 15 kA. In addition, the obtained data show that the joint resistance is increased with current at low current and converged to a certain value. Furthermore, decay time constant of shielding currents induced in the lower joint by shut-off of the external field coils is gradually elongated with decrease of the shielding currents, which suggests that the joint resistance is lower at low current.

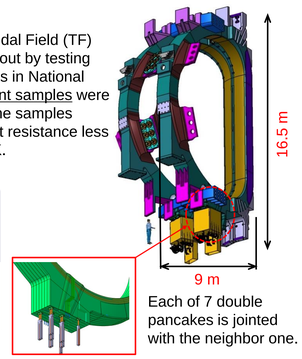
1. Introduction

<Background>

Qualification tests of the ITER Toroidal Field (TF) conductor joints have been carried out by testing short joint samples with test facilities in National Institute for Fusion Science. Ten joint samples were tested until 2019 summer, and all the samples satisfied the requirement of the joint resistance less than 3 nΩ at 2 T and at 4 K and 6 K.

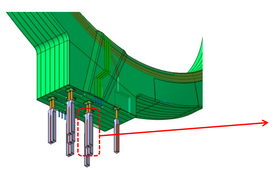
<Research Objectives>

The features of joint resistance of ITER-TF joint samples are summarized, and the DC voltage distribution among the voltage taps on a large CIC conductor is discussed.



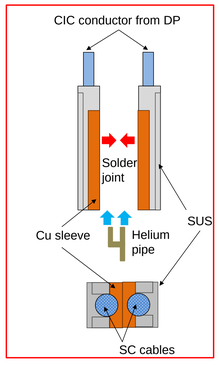
Each of 7 double pancakes is jointed with the neighbor one.

Joint of ITER-TF Coil

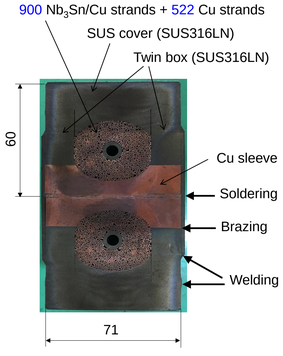


- At the end of each DP, the SC cable is compacted and sandwiched with a SUS cover and a Cu sleeve.
- A pair of Cu sleeves is jointed with solder, and outlet pipes are attached at the end.
- Measurement of the joint resistance are carried out before production of each TF coil.

Main purpose of the qualification test is to confirm the joint resistance between the SC cable and Cu sleeve.



Twin-box Joint

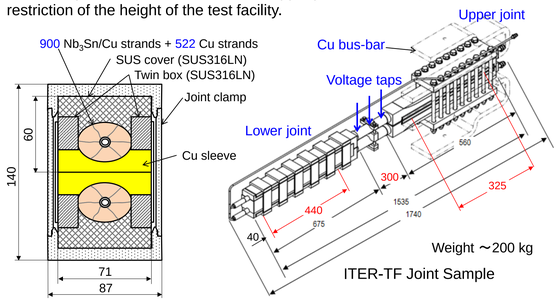


- At the joint region, the conduit, cable wrap, and sub-cable wraps are removed. The Cr coating of the cable surface is also removed. The next, the cable is compacted from the void fraction of 33% to 25%.
- The cable is pressed to a copper sleeve by welding the SUS cover to the twin-box. The cable is sintered to the copper sleeve through the heat treatment for the production of A15 phase.
- The copper sleeve is connected to another one using solder.

2. Joint Sample Test

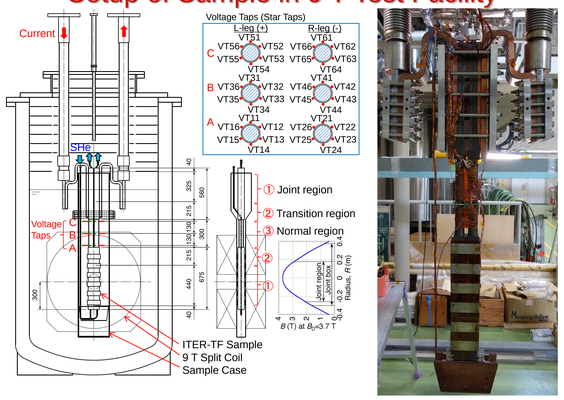
◆The lower joint is a testing part. The length of the contact area of the lower joint is 440 mm, which equals the final cabling pitch.

◆The length of the contact area of the upper joint is 325 mm, due to the restriction of the height of the test facility.



ITER-TF Joint Sample

Setup of Sample in 9 T Test Facility

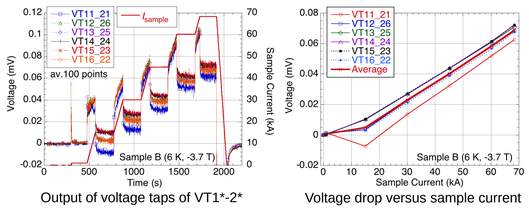


Method to Evaluate Joint Resistance

(1) Each average voltage in the six star taps for the last 30 s in each holding current at 0, 1, 15, 30, 45, 60, 68 kA is derived.
(2) The joint resistance is estimated from the incline of the regression line of the average voltages except for 0 and 1 kA versus the currents.

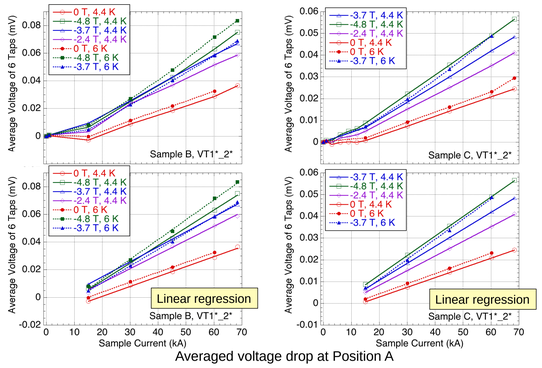
a) The difference among the voltages of six star taps is less than 0.02 mV. The difference is saturated at the current less than 15 kA.

b) The voltage rise at less than 15 kA is considered to be small.



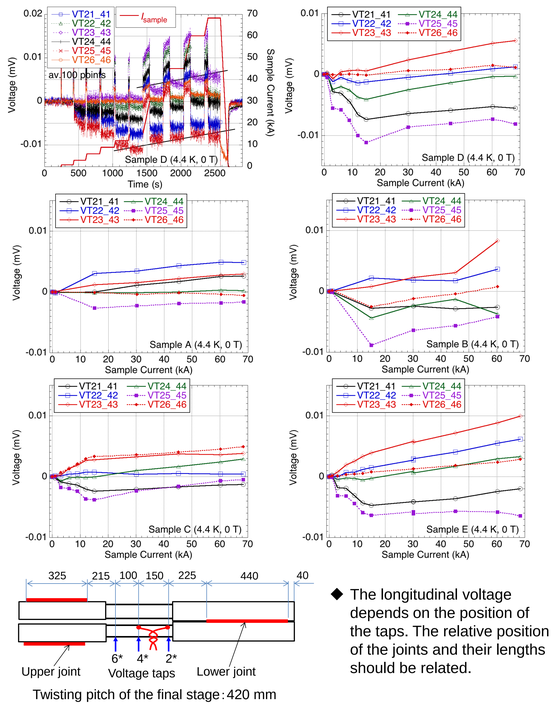
Output of voltage taps of VT1*-2* | Voltage drop versus sample current

Average Voltage Drop of Six Taps



Averaged voltage drop at Position A

Longitudinal Voltage Drop (VT2*-4*)



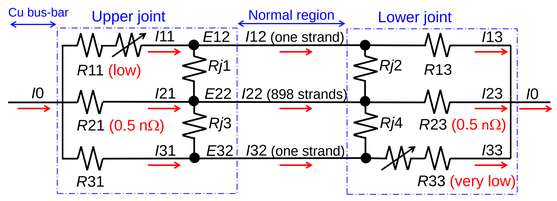
Twisting pitch of the final stage：420 mm

◆ The longitudinal voltage depends on the position of the taps. The relative position of the joints and their lengths should be related.

◆ The difference in longitudinal voltages is enlarged to 0.02 mV at less than 15 kA, and the difference is saturated at the higher currents.

◆ Positive voltage rise of 0.002- 0.005 mV/60 kA at higher than 15 kA should be caused by the currents in conduit.

3. Simulation and Discussion



◆ Since the overall resistance is nonlinear, it is assumed that few strands reach the critical current. Therefore, the joint resistances between Cu sleeve and strands, *R*11 and *R*33 are set at very low resistance.

◆ The joint resistance of the other strands (898 strands), *R*21 and *R*23 are set at 0.5 nΩ from the typical measured resistance. *Rj*1, *Rj*2, *Rj*3, and *Rj*4 are interstrand contact resistances, which are set the same value, *Rj*.

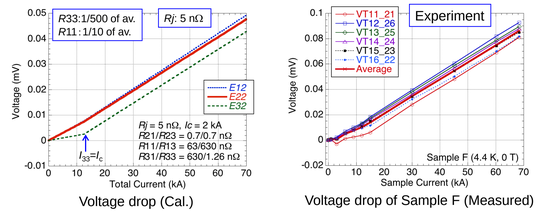
◆ When a current of a strand reaches the critical current, *Ic*, its current is fixed to *Ic* and the resistance is changed to a variable.

Calculation Results

◆ Assuming that the strand with the lowest joint resistance reaches *Ic*, the saturation of voltage difference can be simulated.

◆ The highest voltage difference depends mainly on the interstrand contact resistance, *Rj* and on the critical current, *Ic*.

◆ In the case that *R*33 is 1/500 of the average (~1 nΩ), the saturation at 10 kA can be simulated.

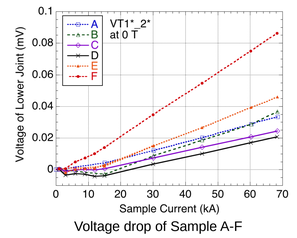


Voltage drop (Cal.) | Voltage drop of Sample F (Measured)

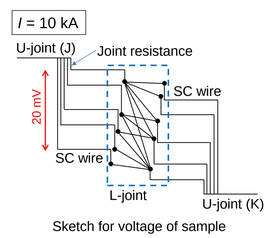
Joint Resistance at Low Current

◆ Behavior of the voltage at low current is different among the samples. The average of six taps shows negative value below 15 kA in few samples.

◆ The differences of joint resistances between the strands and the copper sleeves of the upper joints induce the longitudinal voltage distribution in the copper sleeve of the lower joint. Negative voltage is induced on some pairs of taps.



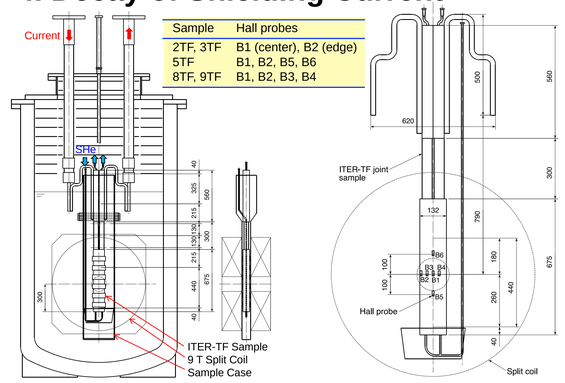
Voltage drop of Sample A-F



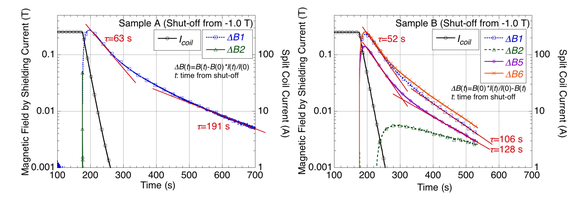
Sketch for voltage of sample

4. Decay of Shielding Current

Sample	Hall probes
2TF, 3TF	B1 (center), B2 (edge)
5TF	B1, B2, B5, B6
8TF, 9TF	B1, B2, B3, B4



Decay of Shielding Current（2TF, 3TF）



◆ B1 measures mainly a loop current flowing in two conductor crossing the joint. The inductance estimated from the time constant at the beginning of the decay and the measured joint resistance is reasonable.

◆ Decay time constant of shielding currents is gradually elongated with decrease of the shielding currents, which suggests that the joint resistance is lower at low current.

◆ Estimated loop current is in the range of 50 kA.

Summary

➢Ten joint samples of ITER-TF coil were tested until 2019 summer. All the samples satisfied the required joint resistance of 3 nΩ at 2 T.

➢The difference among the voltages of the six taps on a CIC conductor is enlarged to the range of 0.01 mV and saturated. The voltage differences are caused by the variation of joint resistances between each strand and the copper sleeve of the joints. The highest voltage is limited with the critical current and the contact resistance among the strands at the joint.

➢Decay time constant of shielding currents induced in the lower joint by shut-off of the external field coils is gradually elongated with decrease of the shielding currents, which suggests that the joint resistance is lower at low current. This phenomenon can be simulated by the assumption of existence of a few strands contacted to the copper sleeve with extremely low joint resistance.