MT25-Wed-Af-Po3.02-06

New inspection method of joint resistance at room temperature for ITER TF Coil

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1. Background

The ITER TF coil consists of several superconducting conductors wound to D-shape, called as double-pancake (DP). The adjacent DPs are electrically connected via joints. This joint resistance (R_j) should be sufficiently small such as several nano-ohm. The soundness of R_j is confirmed by full size joint sample (FSJS) test performed in National Institute for Fusion Science (NIFS), in addition to the severe process control during the joint fabrication. However, of course, it is more effective if the soundness of real TF joints can be confirmed directly. This will be able to reduce the risk of high Joule heating at joint in TF coil operation. However, R_j measurement on TF coil is not practical from viewpoint of schedule and cost because huge equipment to cool down the whole of TF coil to 4 K is necessary in terms of huge mass and size of TF coil.

2. Objectives

- Development of the simple inspection method for real TF joint, which enables to detect some abnormality in the joint at room temperature.
- Investigation of the validity and sensitivity of this developed method.

7. Conclusion

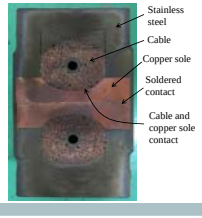
- The newly inspection method for soundness of fabricated TF joint was developed. This method is to acquire of voltage profile of copper sole of joint box at room temperature during charging 20 A of current into copper sole and then evaluate the gradient of voltage profile, *dV/dz*.
- The measurements were performed for real TF joints and NIFS FSJS before excitation. All of measurement results of real TF joints were repeatable and agreed with one of NIFS FSJS, whose joint resistance had been known as good in FSJS test. From this results, it could be confirmed that real TF joints are also good as same as NIFS FSJS. Thus, validity of this developed inspection could be confirmed.
- To see the sensitivity of this developed inspection, the measurement for NIFS FSJS after excitation, whose condition of cable in the joint was slightly changed due to electromagnetic force in the FSJS test, was also performed. As a result, significant difference on evaluation of *dV/dz* was seen in FSJS after excitation compared with FSJS before excitation. This is because current distribution inside joint was changed before and after excitation.
- Thus, it can be said that the developed inspection method is very sensitivity even for small disturbance of condition inside joint. If there is some abnormality in the fabricated joint, the abnormality will be able to be detected.

3. ITER TF joint

Joint Configuration

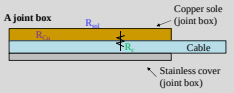
- The joint boxes, which consists of explosion bonded copper sole and stainless steel box, are assembled at the both ends of DP.
- The cable, which consists of 900 superconducting and 522 copper strands, is inserted into the joint box. Then the cable is compacted from the void fraction of 33 % to 25 %.
- After completion of the joint box fabrication, the joint is heat-treated with the DP to react superconducting materials. Then, the adjacent joint boxes are electrically connected by soldering between the copper soles.

Conductor	
Cabling layout	$(3^{11}\times3\times5\times\text{core}^{29})\times6$
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	
Over all of joint length	675mm
Cable compaction length in joint	440 mm
Void fraction	25%
Joint box material(SS part)	316LN
Joint box material(Copper part)	C1020



Joint resistance (R_j)

Joint resistance (R_j)
= resistance of copper sole (R_{Cu}) + resistance of solder (R_{sol})
+ contact resistance between copper sole and cable (R_c)

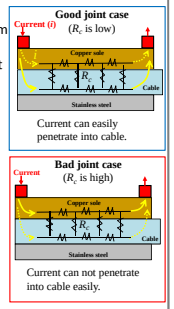


- R_j should be below 3 nΩ in ITER TF joint.
- As R_{Cu} is considered to be sufficiently small and R_{sol} can be controlled to by process control and visual check during the soldering, these are not significant issues.
- In contrast, it is impossible to check the soundness of R_c although there is possibility that R_c may be sensitive to even slight contaminant through manufacturing process.
- Thus, as there is uncertainty in R_c, we focused on development of inspection method of R_c.

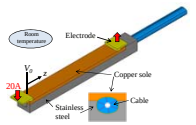
4. Inspection Method

Concept

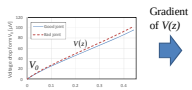
- When current flows into copper sole from the end to end, difference of current distribution inside joint is observed depending on a degree of R_c.
- This difference may be observed by measuring voltage profile of copper sole.



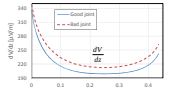
Preliminary analysis



- To investigate degree of difference between good and bad joint in voltage profile of copper sole, calculation was performed initially.
- As a result, evaluation of gradient of voltage profile is very effective.



Gradient of $V(z)$

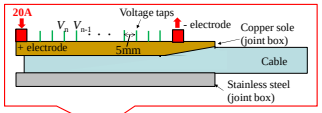


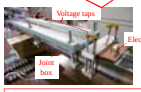
Difficult to distinguish the difference

The difference could be distinguished over the whole length.

Measurement system

- To evaluate *dV/dz*, the measurement system to acquire voltage profile of copper sole was developed.





$$\frac{dV}{dz} = \frac{V_n - V_{n-1}}{\Delta z}$$

Adjacent measured voltages

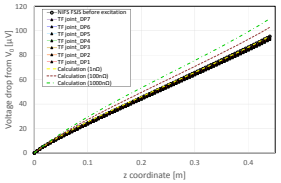
5mm

- Voltage taps are attached on the copper sole at intervals of 5 mm.
- 20 A of current is charged at room temperature.
- Local steepness of voltage profile, *dV/dz*, is evaluated discretely .

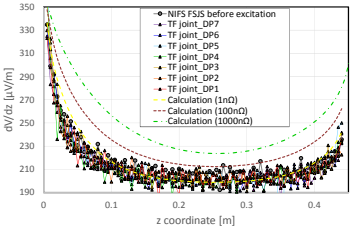
5. Results

Measurements of real TF joints and NIFS FSJS

- Measurements were performed for seven real TF joints and NIFS FSJS before FSJS test (before excitation).
- As R_j could be measured in NIFS FSJS, soundness of TF joints could be confirmed by comparing R_j values obtained.
- Timing of inspection is just after heat treatment for both the FSJS and TF joints.



***dV/dz* evaluation**



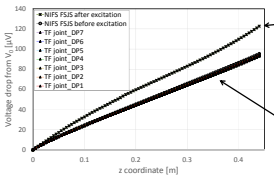
Measurement results of *dV/dz* as a function of *z* coordinate. Triangle pointed lines are results of real TF joints and round pointed line is result of NIFS FSJS before excitation. Dotted lines are calculation results based on last section as references.

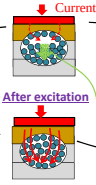
- All of results were in good agreement with calculation of good joint case (1nΩ). In addition, all of results of TF joints were repeatable and agreed with one of NIFS FSJS. As it was revealed that R_j of FSJS was 1.1 nΩ, *i.e.* good joint, in FSJS test, it could be said that TF joints were also good joints.
- From these results, soundness of real TF joints were confirmed and the validity and utility of this developed inspection method were shown.

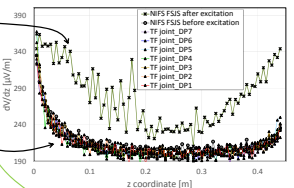
6. Sensitivity of this inspection

Comparison of FSJS before and after excitation

- To see the sensitivity of developed inspection method, an additional inspection was performed. This test was to perform the inspection for NIFS FSJS, which was already excited in FSJS test.
- Condition of cable in the joint is changed by electromagnetic force during excitation in FSJS test, although the joint resistance is not degraded by this electromagnetic force. However, this small change in the joint may affect. If this is the case, quite small change in joint should be detected by the method newly proposed by the authors.
- So, by comparing *dV/dz* on NIFS FSJS before and after excitation, the inspection sensitivity can be seen.







Strands are pushed by electromagnetic force during excitation.

- Significant difference was seen on FSJS after excitation compared with FSJS and TF joints before excitation, while such a big difference was not expected. It is assumed that because strands inside cable have been slightly moved and detached from each other by pushing of electromagnetic force, current has become more difficult to penetrate into cable in FSJS after excitation.
- Thus, developed method is very sensitive to the change in condition of inside joint. From this result, it can be said that if there is some abnormality in the fabricated joint, the abnormality can be detected.

Presented at the Magnet Technology Conference , 2017 Oct. 30, Amsterdam, Netherland; Session: 6-B-1 Superconducting Magnets for Fusion; Program I.D. number: MT25-Wed-Af-Po3.02-06