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Test of ITER-TF Joint Samples with NIFS Test Facilities

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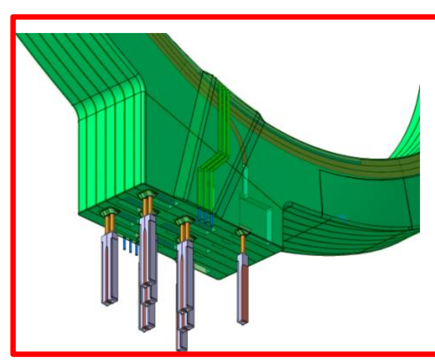
Background and Objectives

<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. Five joint samples were tested until 2016, 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.

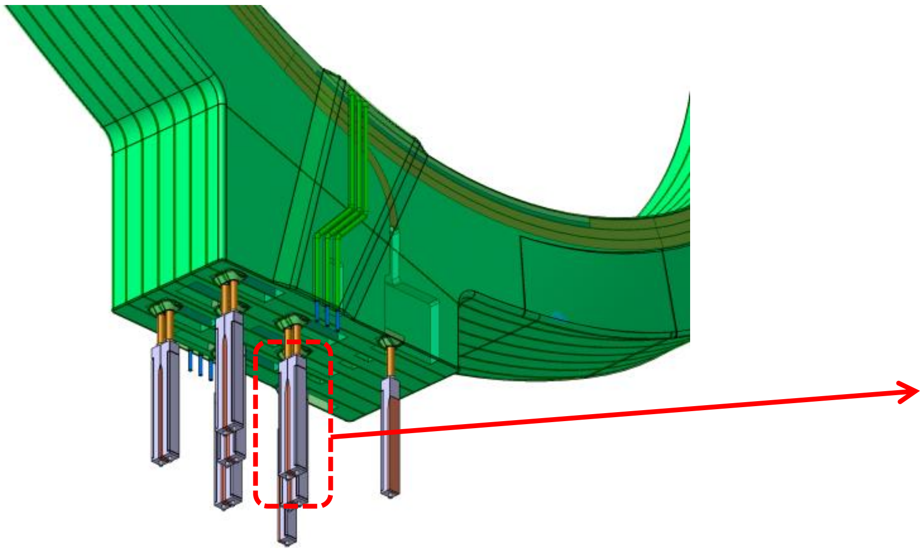
<Research Objectives>

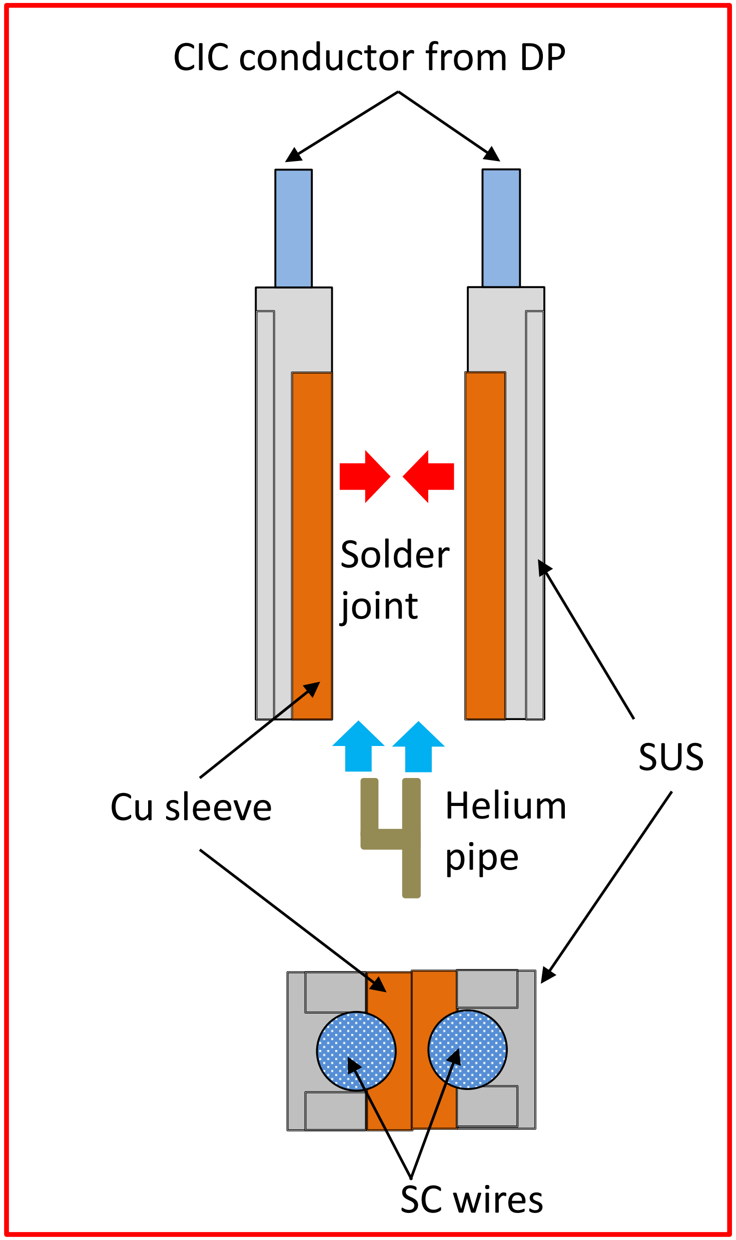
The features of measured data of the joint resistance of large CIC conductors are summarized, and the voltage distribution among the voltage taps is discussed.



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

Joint of ITER-TF Coil

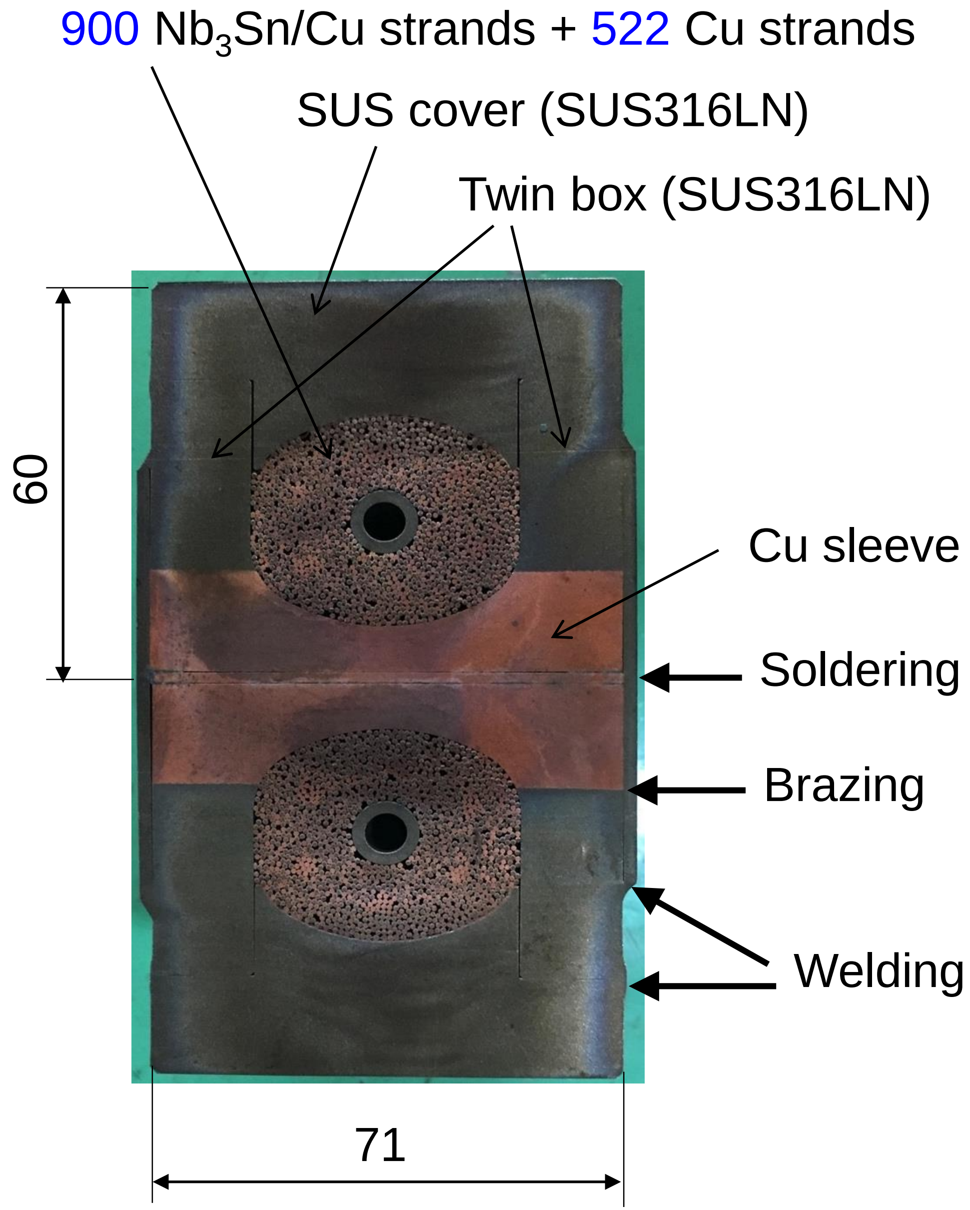




- At the end of each DP, SC wires are compacted and sandwiched with a SUS cover and a Cu sleeve.
- A pair of Cu sleeves is jointed with solder, and outlet pipes are attached at the end.
- Measurement of the joint resistance are carried out before production of each TF coil.

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

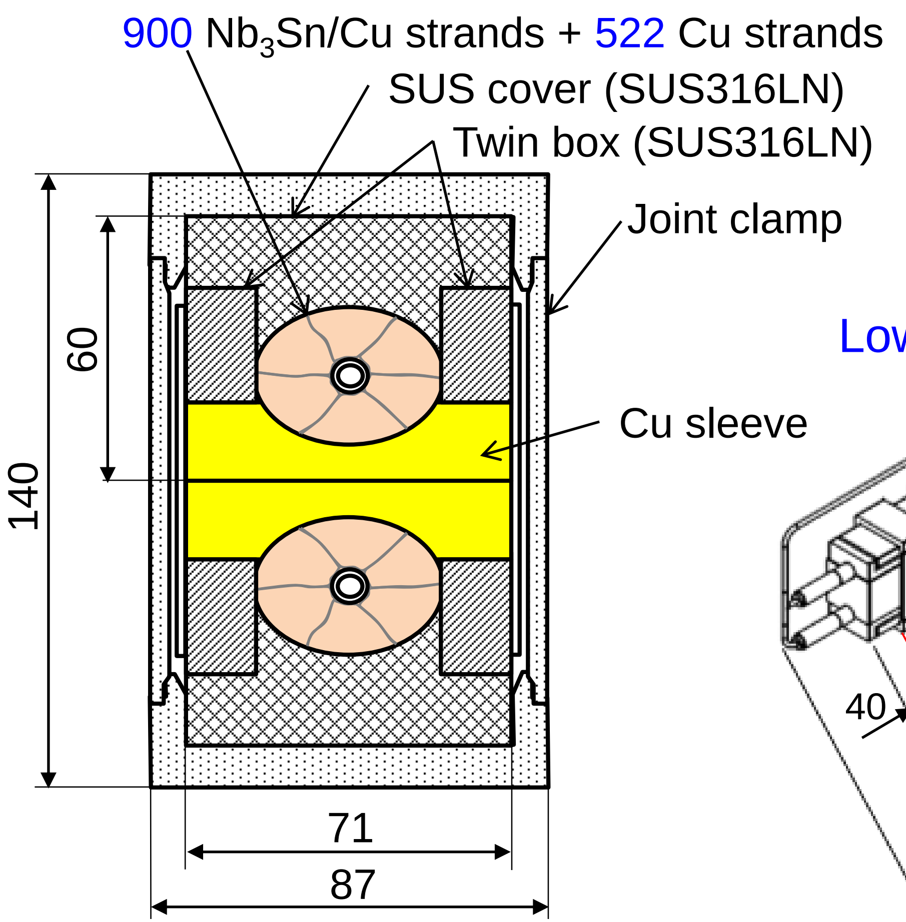
Twin-box Joint

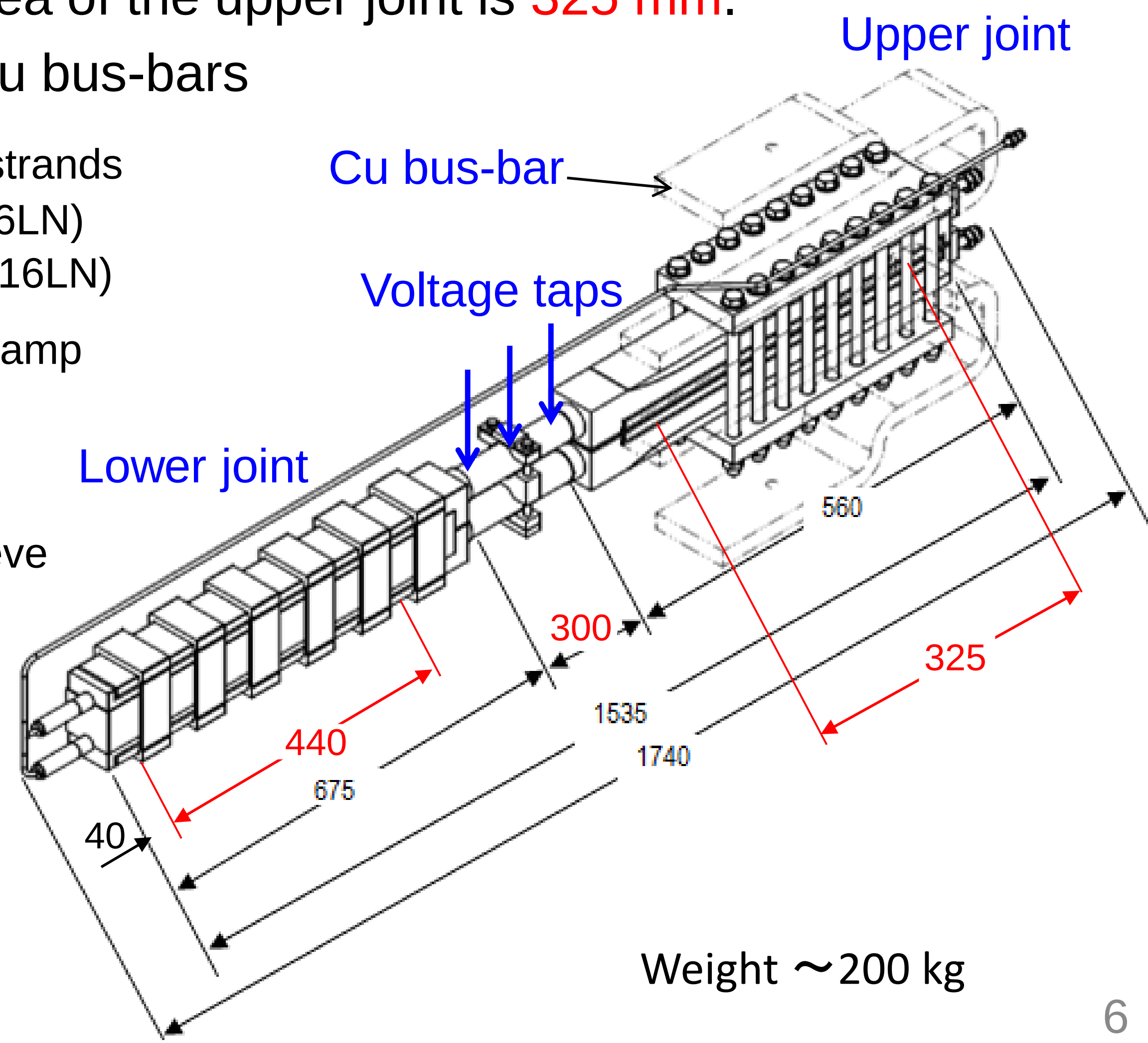


- At the joint region, the conduit, cable wrap, and sub-cable wraps are removed. The next, the cable is compacted from the void fraction of 33% to 25%, and the Cr coating of the cable surface is removed.
- The cable is pressed into a stainless steel (SS) box and brazed to the copper sleeve, the surface of which is machined after heat treatment. The copper sleeves are connected to one another using solder.

ITER-TF Joint Sample

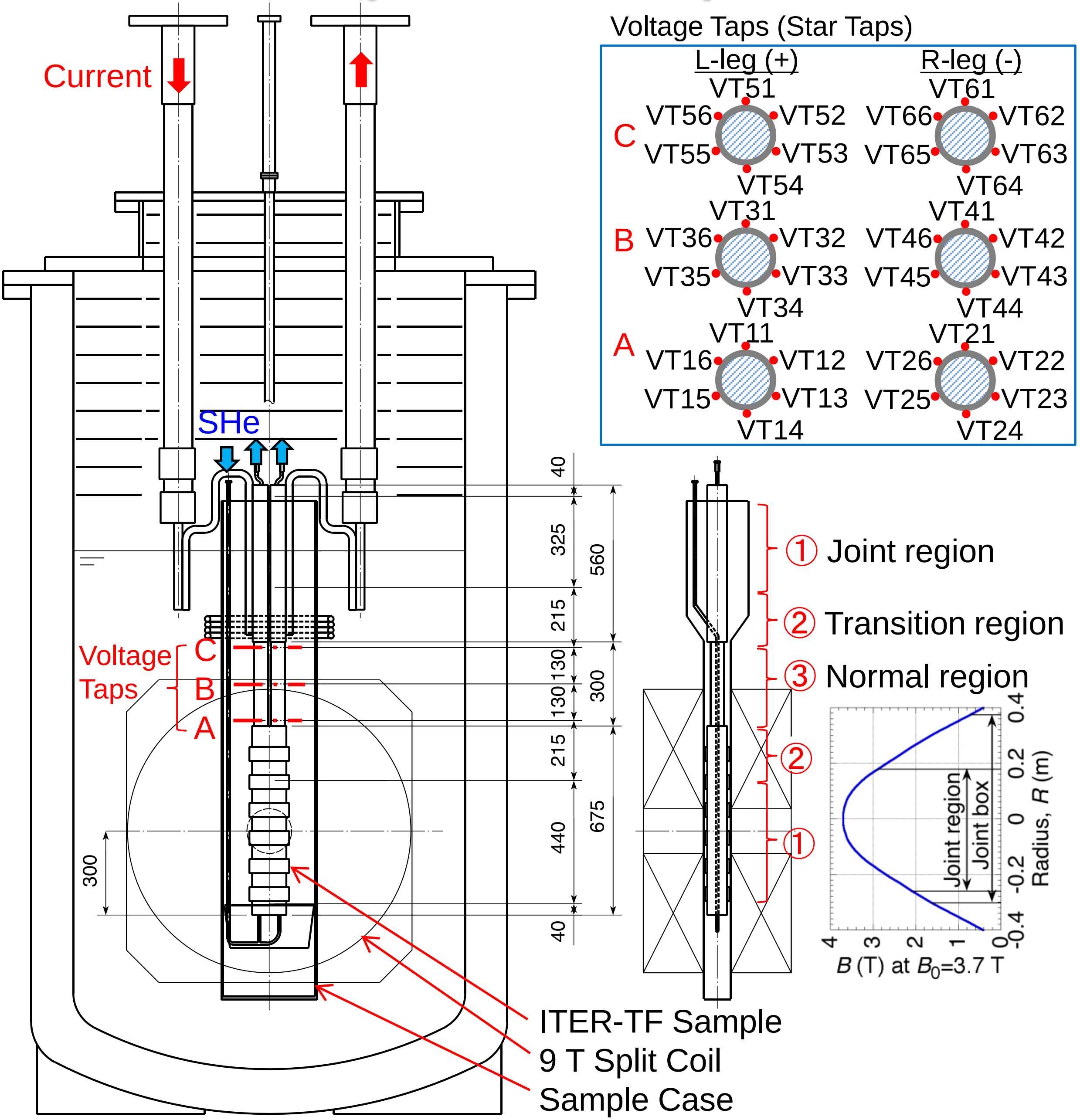
- The length of the contact area of the lower joint is 440 m, which equals the final cabling pitch.
- The length of the contact area of the upper joint is 325 mm.
- SC wires are attached on Cu bus-bars





Weight ～200 kg

Setup of Sample in 9 T Test Facility



Test Items & Conditions

Sample flow rate：1-3 g/s（manual control）
Inlet pressure of samples：~0.5 MPa
Direction of the background field：Negative (repulsing force)

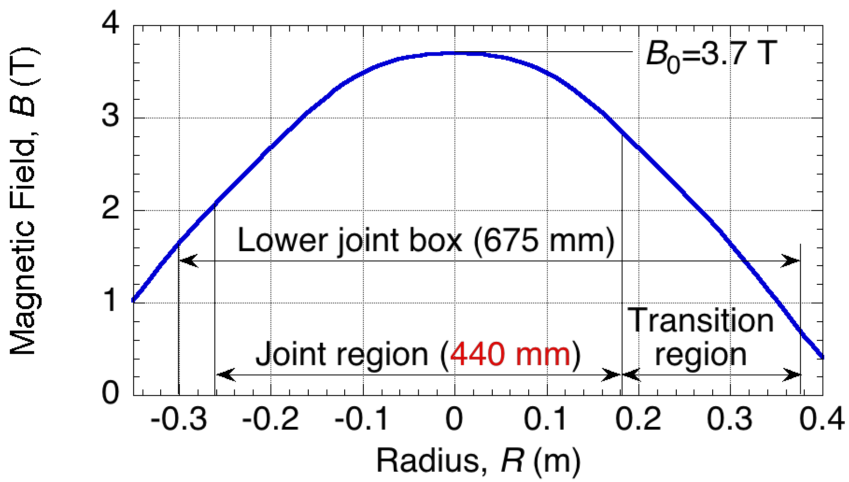
(1) Joint resistance at 4.2 K（Field：0, -2.4, -3.7, -4.8 T）
Charging rate：+150 A/s, -600 A/s
Currents are held for 180 s at 0, 1 kA, 15 kA, 30 kA, 45 kA, 60 kA, 68 kA
（Note）When the background field is changed, the measurement does not start for more than 600 s in order to avoid the effect by shielding current in the samples.

(2) Joint resistance at 6 K（Field：0, -2.4, -3.7, -4.8 T）
Same as (1)

(3) Calibration of calorimetric method

(4) AC loss

(5) Repeated excitations
from 0 to 33.6 kA at -7.5 T

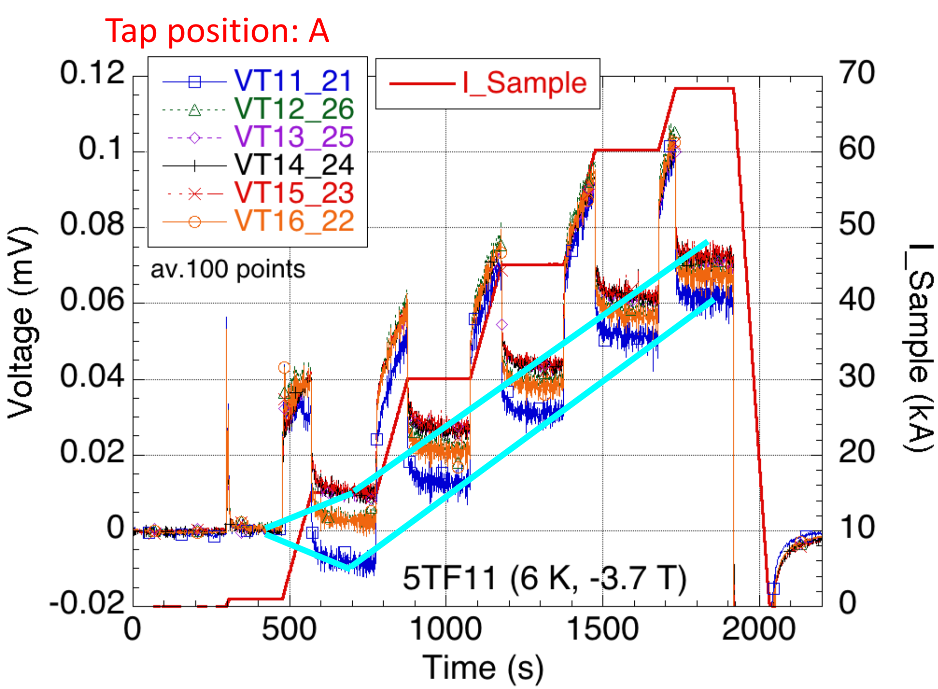


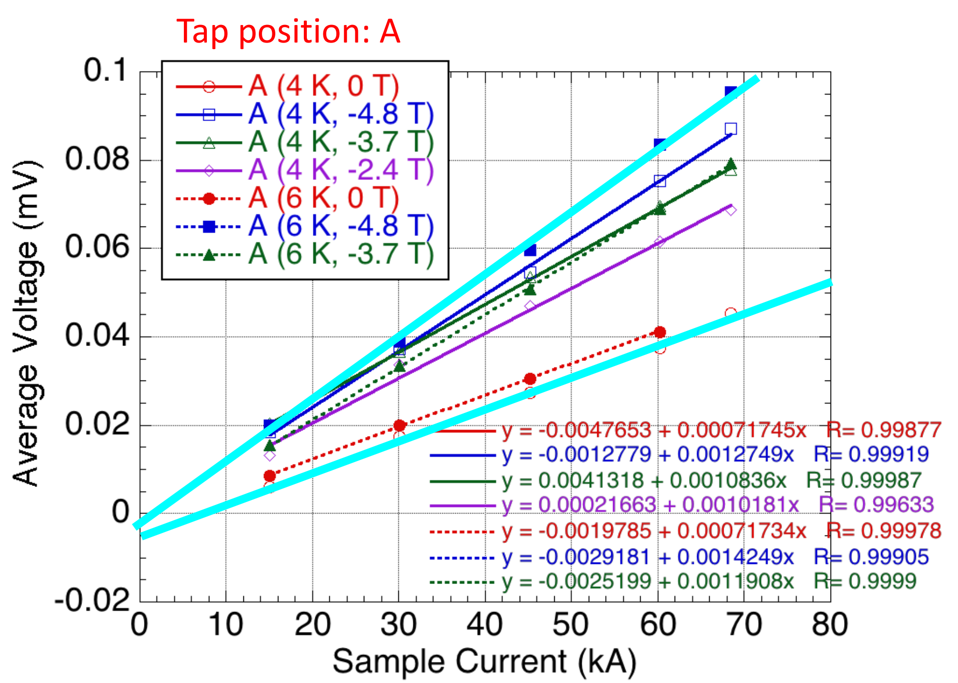
Magnetic field distribution of the split coils

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.

All the five samples satisfied the requirement that the joint resistance is less than 3 nΩ at 2 T. The difference among the voltages of six star taps is less than 0.01 mV. The difference is saturated at the current below 15 kA.



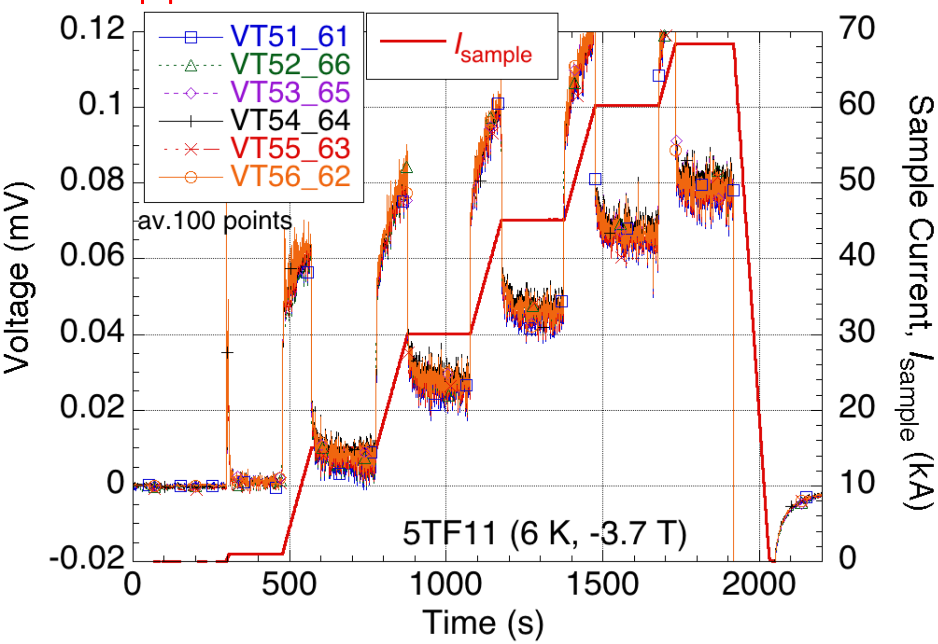


Output of voltage taps of VT1*-2* of TF5

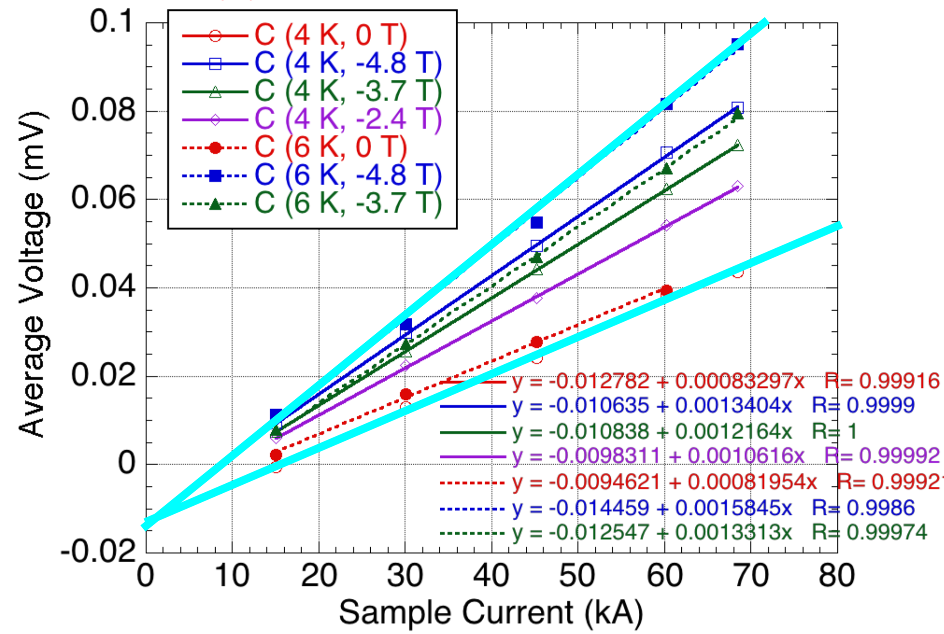
Nonlinear Behavior of VT3-4 and VT5-6

- Left figure shows output of VT5-6 that is located at the upper position. The voltage rise from 1 kA to 15 kA is clearly low than that from 15 kA to 68 kA.
- The average voltages of VT5-6 except for 0 and 1 kA are well fitted by linear line. Since the voltage after discharge recovers to zero, the voltage drift by amplifiers should be small. The voltage rise at less than 15 kA is considered to be small. The similar phenomena is clearly shown at VT5-6 (Position C) and VT3-4 (Position B) in all five samples.

Tap position: C

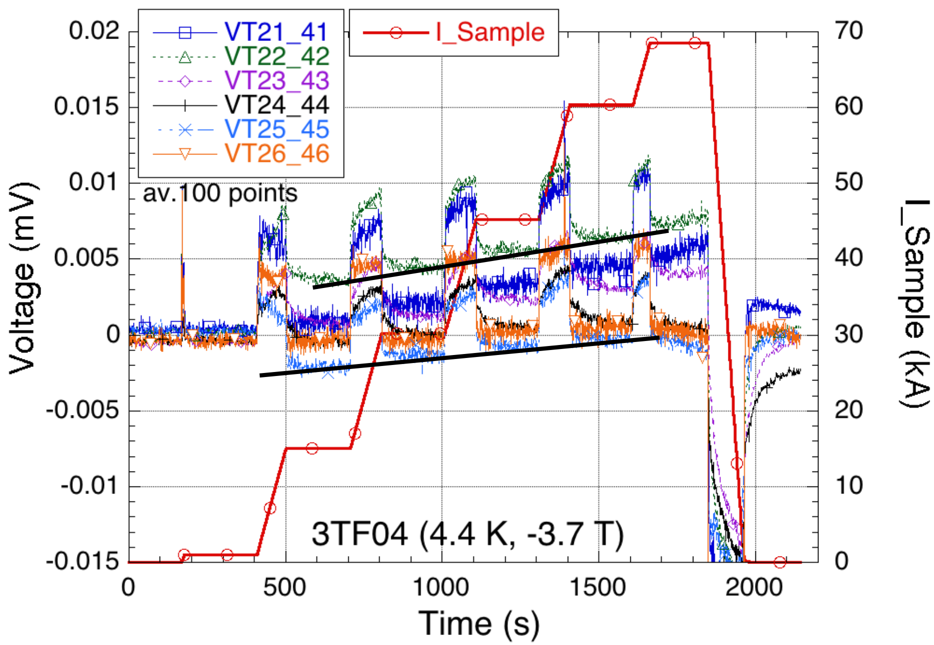


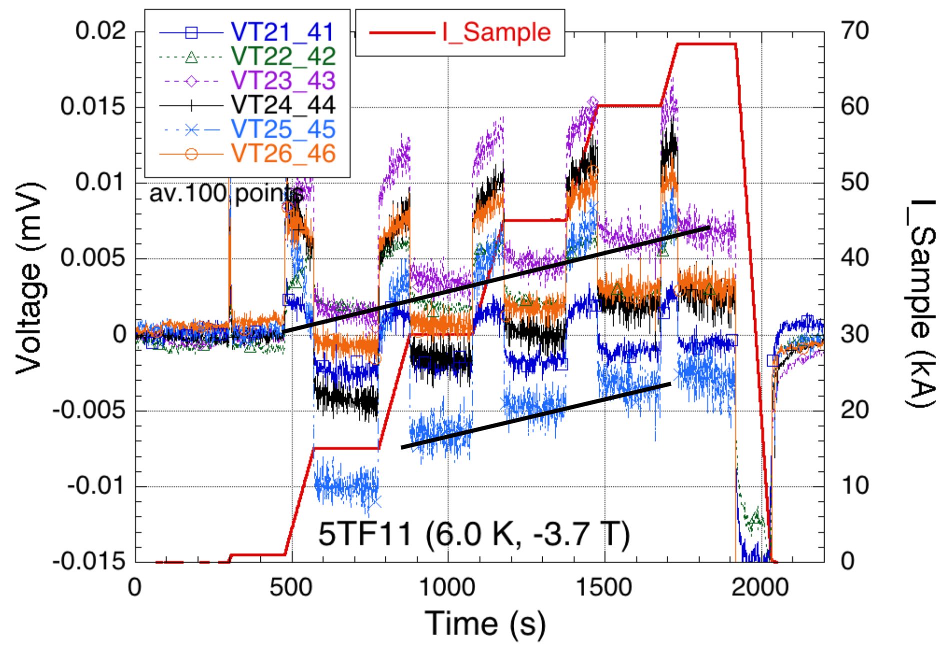
Tap position: C

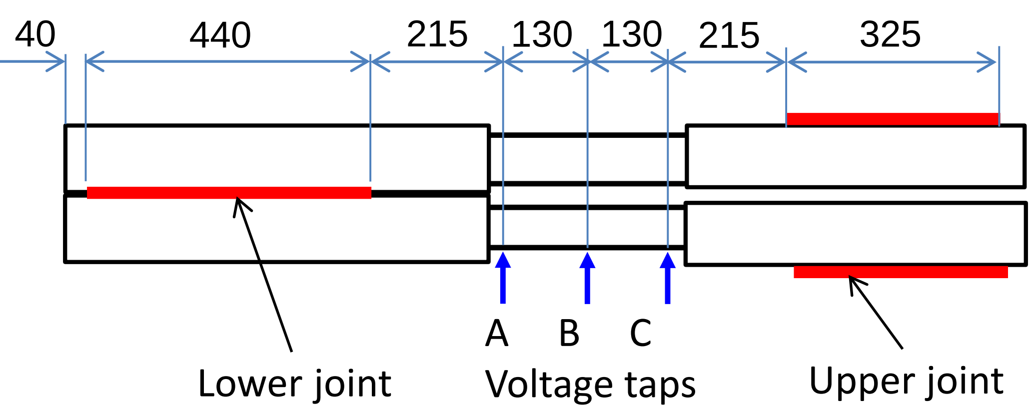


Output of voltage taps of VT5*-6* of TF5

Longitudinal Voltage Drop (VT2-4)

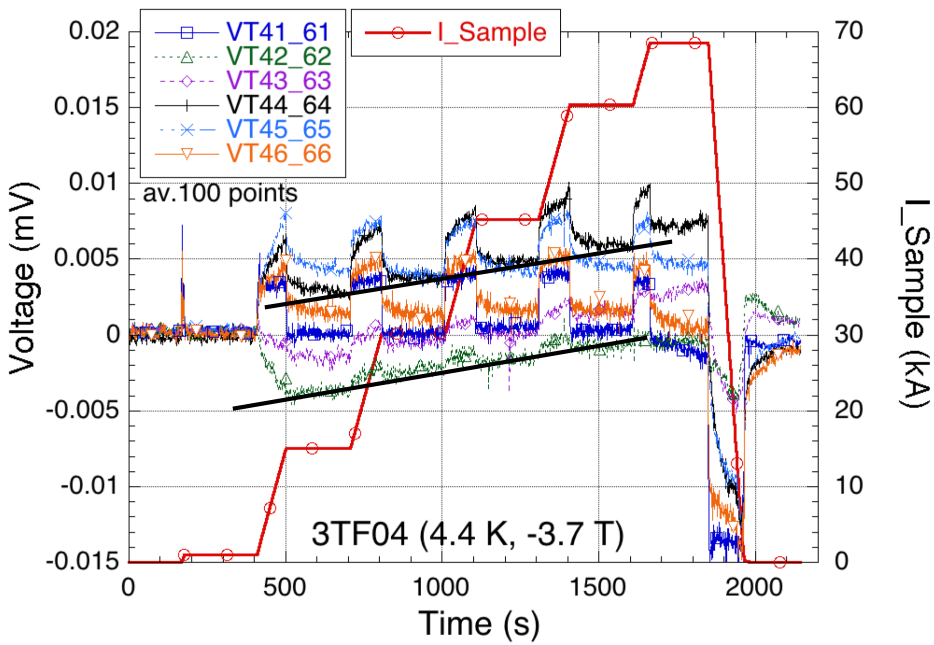


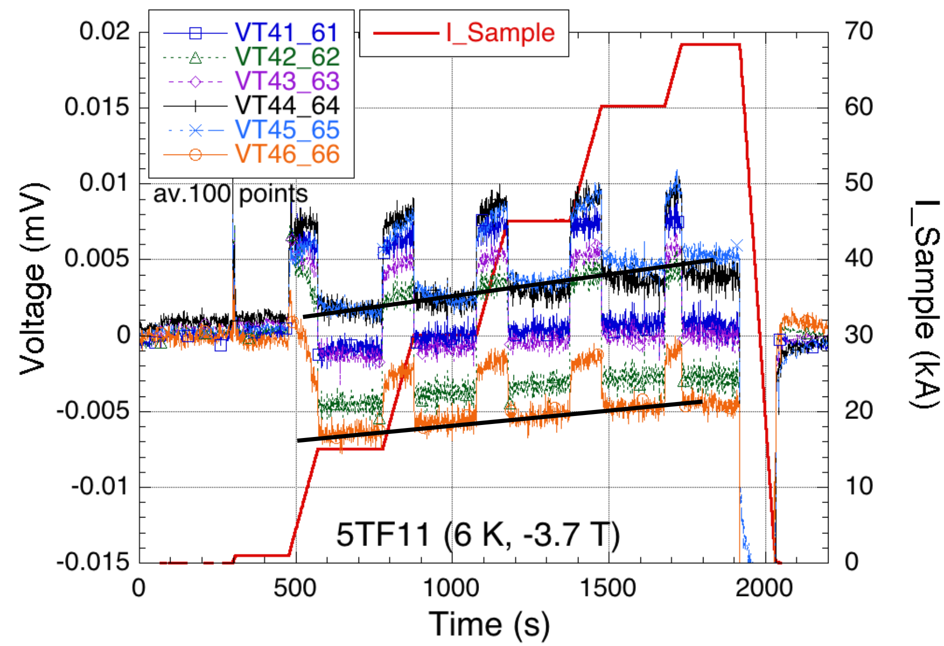


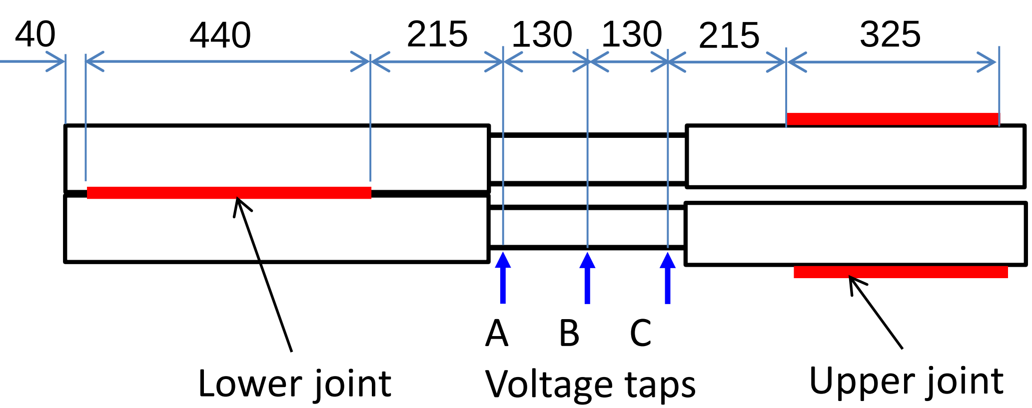


- The difference in longitudinal voltages is enlarged to 0.01 mV at less than 15 kA, and the difference is saturated at the higher currents.
- Positive voltage rise of 0.002-0.005 mV/60 kA at higher than 15 kA should be caused by the currents in conduit.

Longitudinal Voltage Drop (VT4-6)

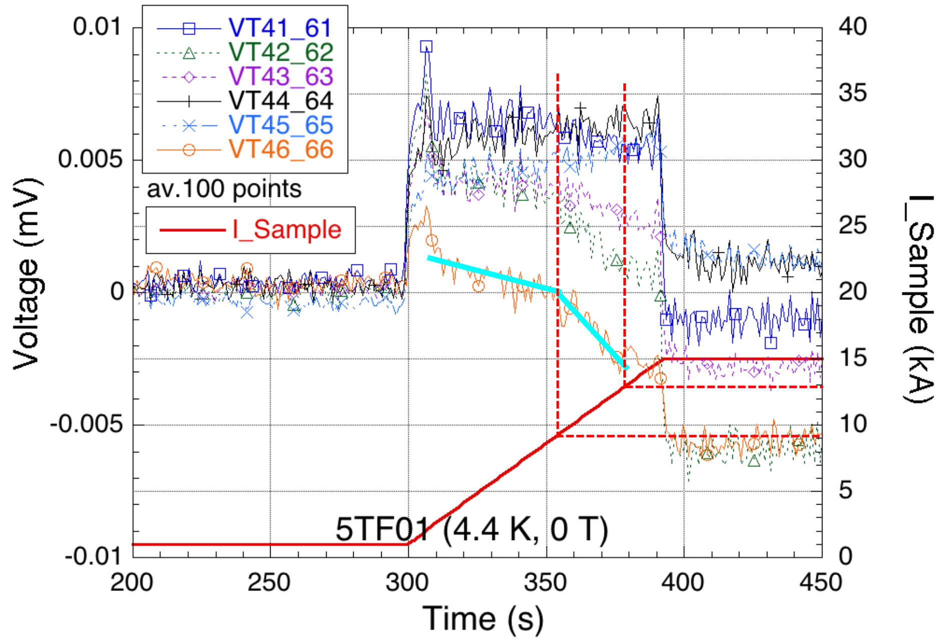


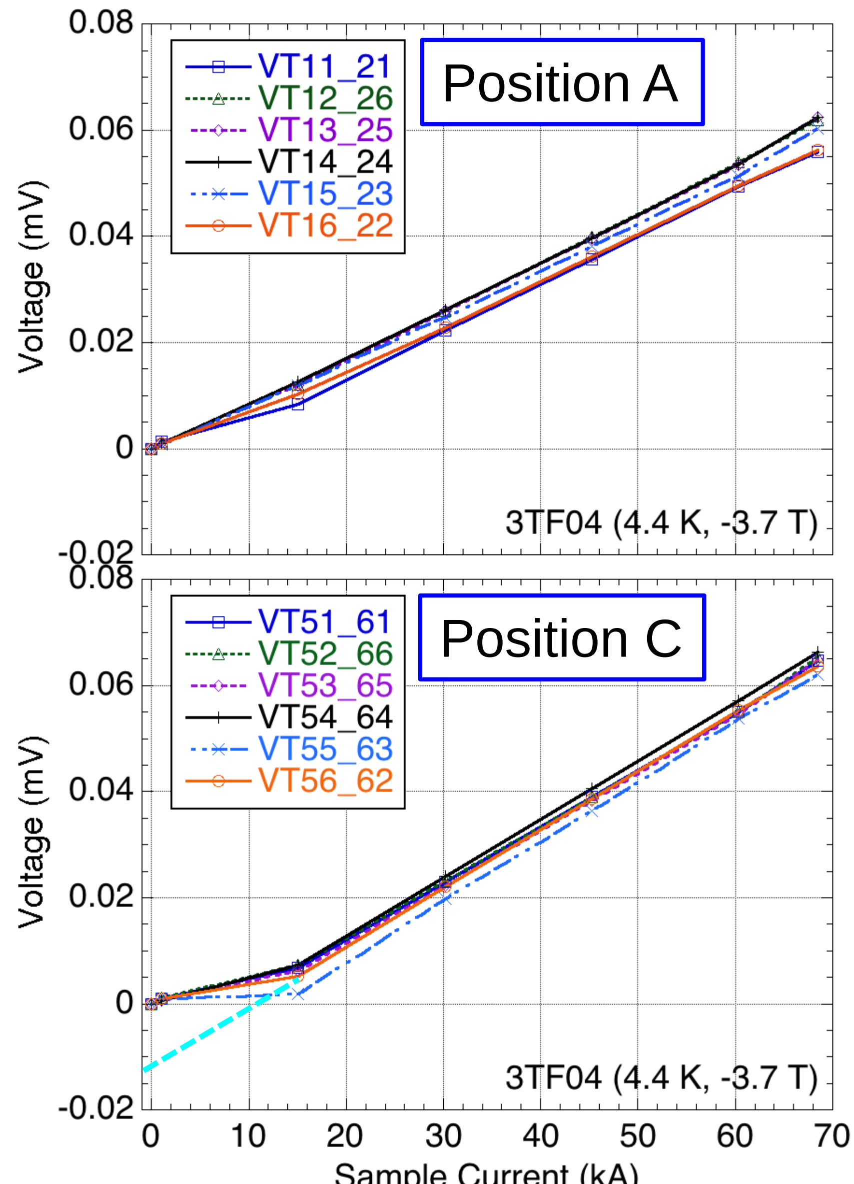




- The behavior of longitudinal voltages at VT4-6 is similar as VT2-4.
- The current flowing pattern is considered to be changed at the current below 15 kA.

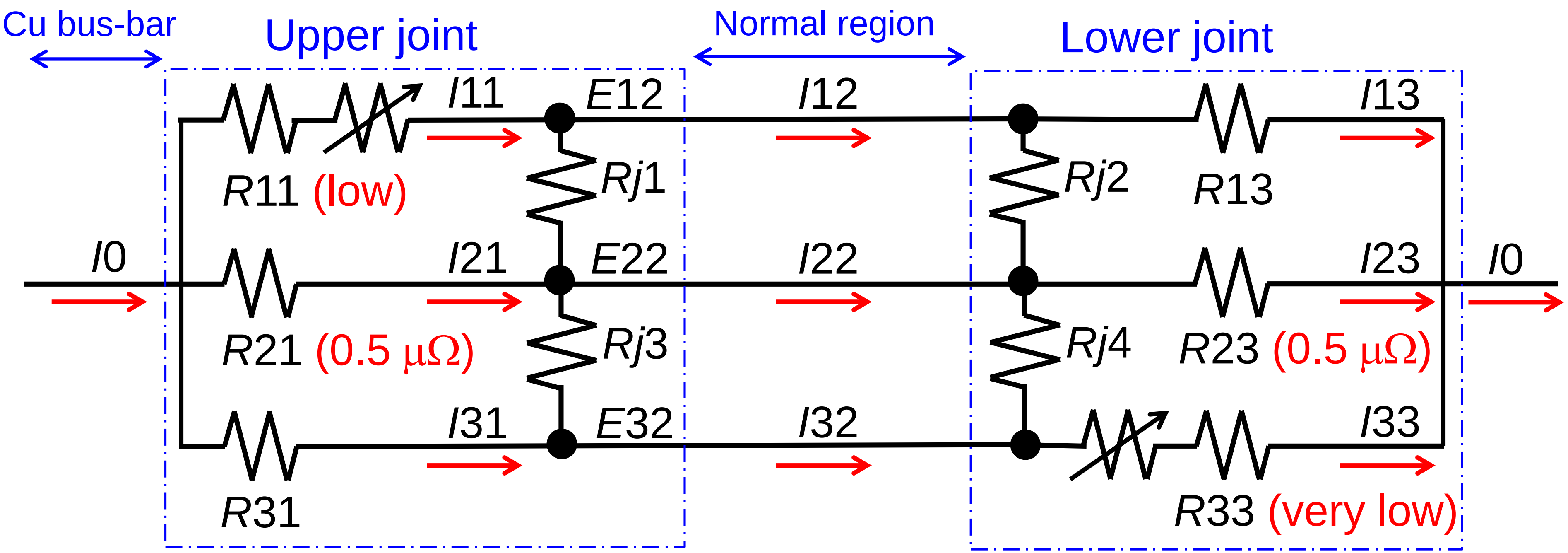
Questions for Voltage in Joint Sample





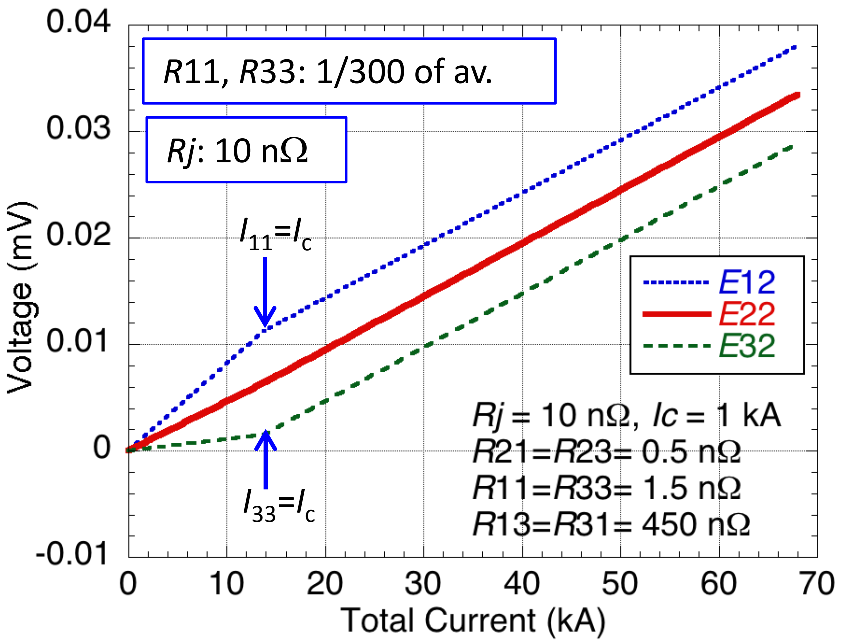
1) Why is the difference of voltages both in cross-section and in longitudinal direction enlarged to 0.01 mV at less than 15 kA and saturated at the higher currents?
2) Why is the voltage rise at low currents small especially at VT5-6 (uppermost taps)?

Circuit Model for Non-uniform Current

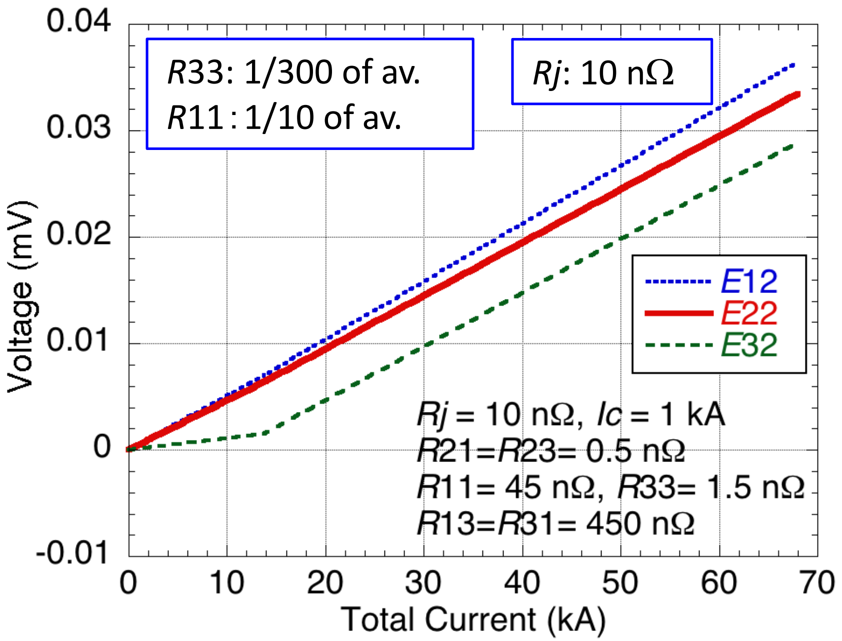


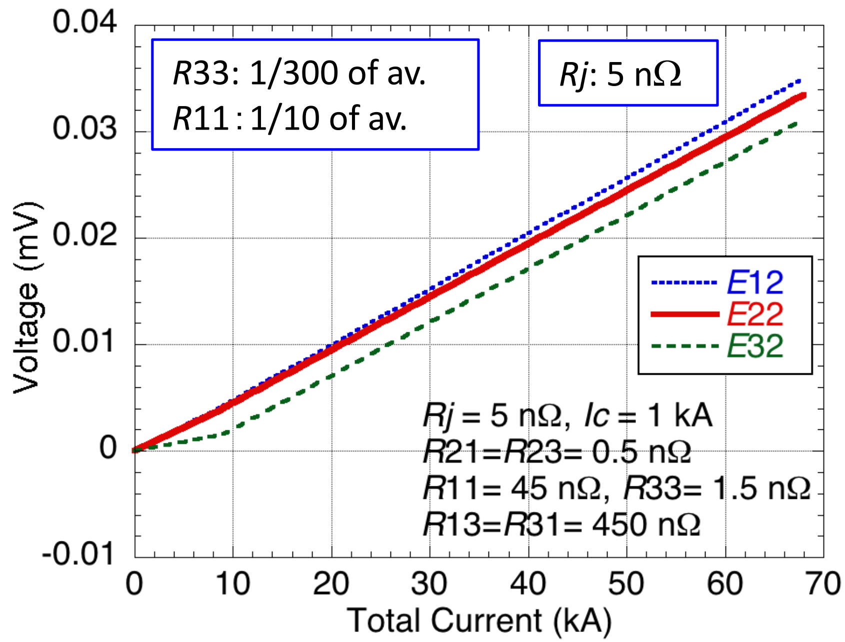
- Since the overall resistance is nonlinear, it is assumed that few strands reach the critical current. Therefore, the joint resistances between Cu sleeve and strands, *R*11 and *R*33 are set at very low resistance.
- The joint resistance of the other strand (almost 900), *R*21 and *R*23 are set at 0.5 nΩ from the measured resistance. *Rj*1, *Rj*2, *Rj*3, and *Rj*4 are the contact resistances between strands.
- When a current of a strand reaches *Ic*, its current is fixed to *Ic* and the resistance is changed to a variable.

Calculated Results

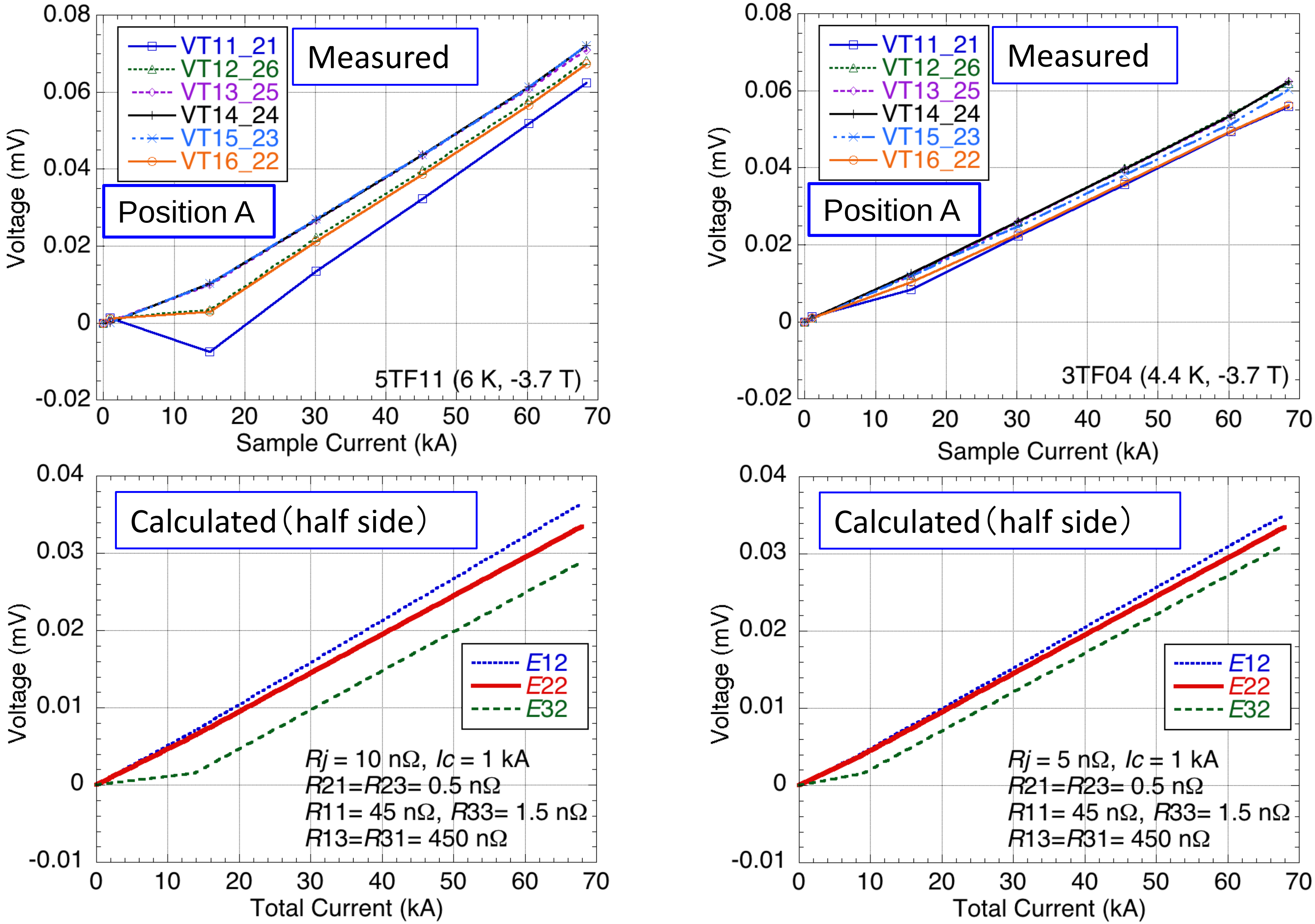


- Assuming that the strand with the lowest joint resistance reaches *Ic*, the saturation of voltage difference can be simulated.
- The max. voltage difference depends mainly on *Rj*.
- In the case that *R*33 is 1/300 of the average, the saturation at 10 kA can be simulated.





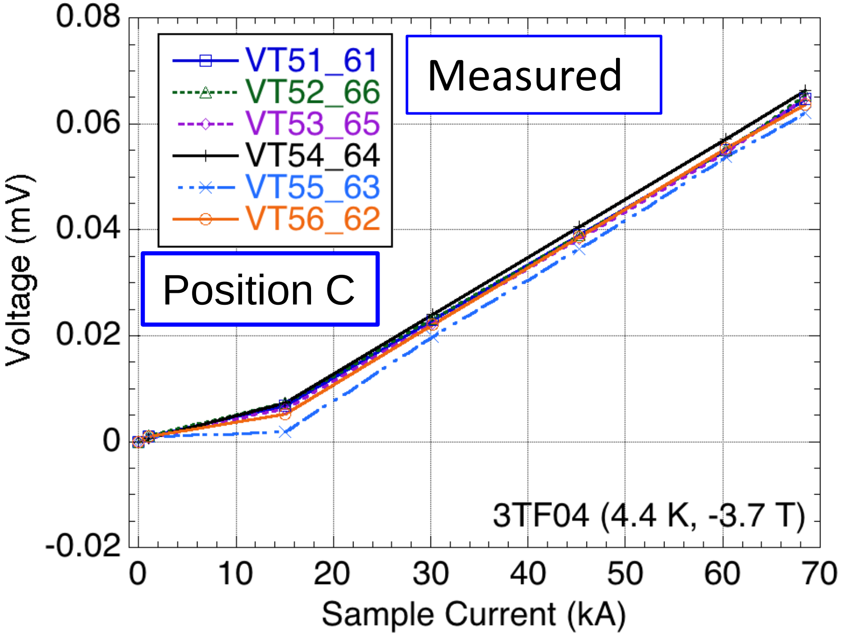
Comparison between Exp. and Cal.

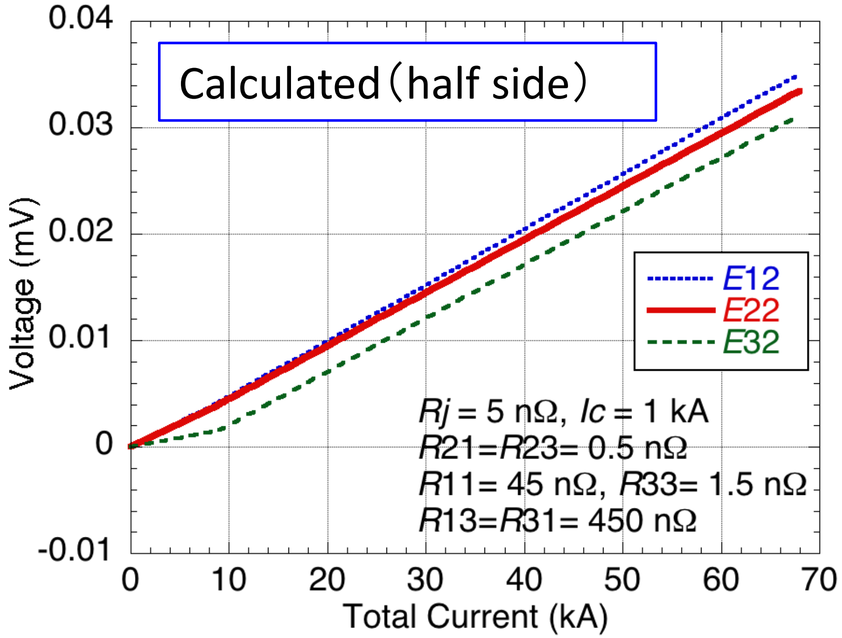


Discussion

- In reality, the interstrand contact resistances, *Rj* are varied, and few strands should reach I_c from the strand with the lower joint resistance and with lower interstrand contact resistances.
- Since *E*22 corresponds to the average voltage, this model can not simulate the clearly low voltage rise at low currents.
- Further research is necessary to explain this phenomenon as well as <u>the difference in tap positions</u>.

Electromagnetic effects may concern the behavior at low currents.





Summary

- The measurement of joint resistance of ITER-TF conductors in nΩ has been successfully carried out by using the test facility with 9 T split coils and the dc 75 kA power supply. The necessary accuracy is attained by adopting star voltage taps and by averaging large data collected with 100 Hz sampling.
- The difference among the voltages of the six taps is enlarged to the range of 0.01 mV and saturated at the current less than 15 kA. A simplified electric circuit model can simulate this phenomenon by assuming existence of a strand contacted to the copper sleeve with a very low joint resistance.
- Further research is necessary to explain the low voltage rise at low currents as well as the difference in tap positions.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.