T_{cs} Measurement Result of ITER Toroidal Field Insert Coil Tested in 2016

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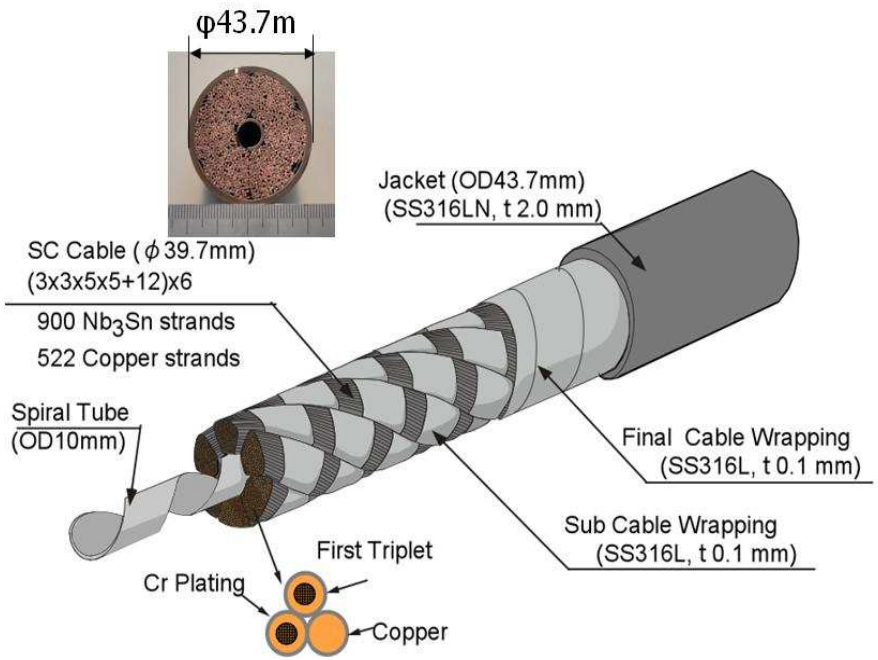
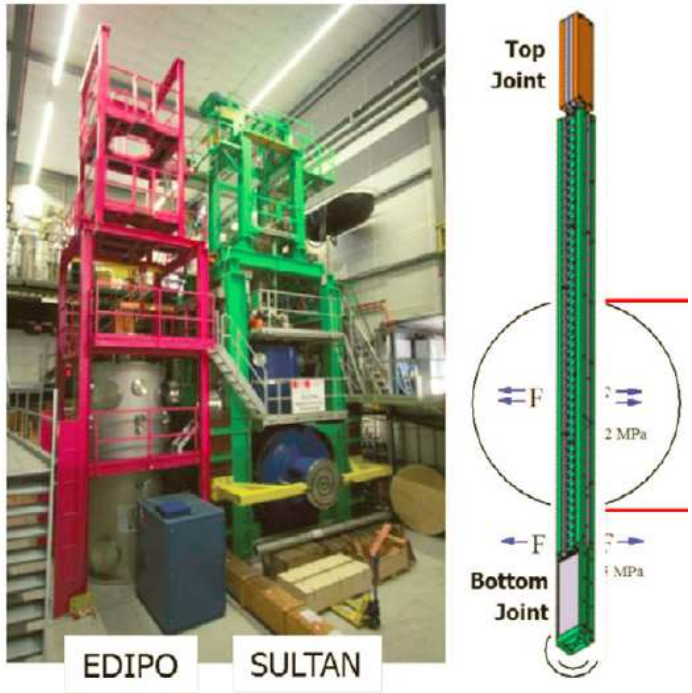
ITER TF Conductor Qualification So Far

A series of ITER Toroidal Field (TF) conductor qualification test has been performed in SULTAN test facility. The sample is 3.6 m straight shape, and high field is generated in 0.45 m region.



ITER TF conductor (Cable-in-Conduit Type)



0.45m
High
Field
Zone

SULTAN Test Facility and its sample shape [1,2]

[1] http://spc.epfl.ch/page-97675-en.html
[2]A. Devred *et al.*, "Challenges and status of ITER conductor production," *Supercond. Sci. Technol.* 27 (2014) 044001.

TF Insert Coil

The TF insert Coil (TFIC) was newly developed in 2014, with the ITER TF conductor which is the same spec for the ITER.

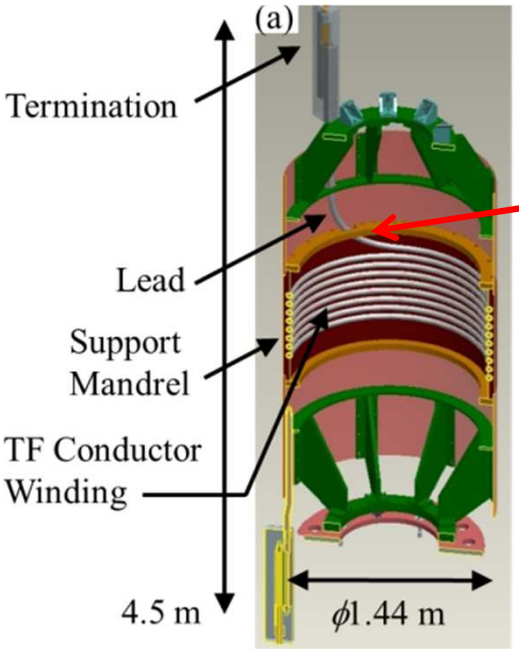
● TFIC Spec.

Coil diameter : 1.44 m

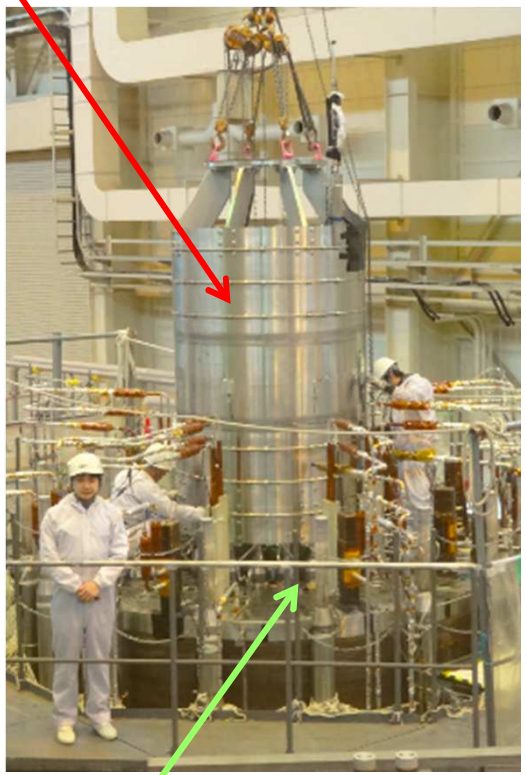
Winding: 8.875 turn single layer solenoid coil

● Test Condition feature:

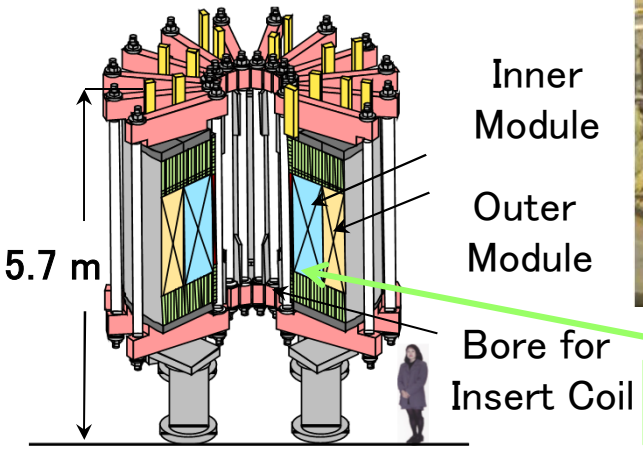
Backup field uniformity +/- 0.5 T along the 35 m TF conductor length



TF Insert Coil (TFIC)

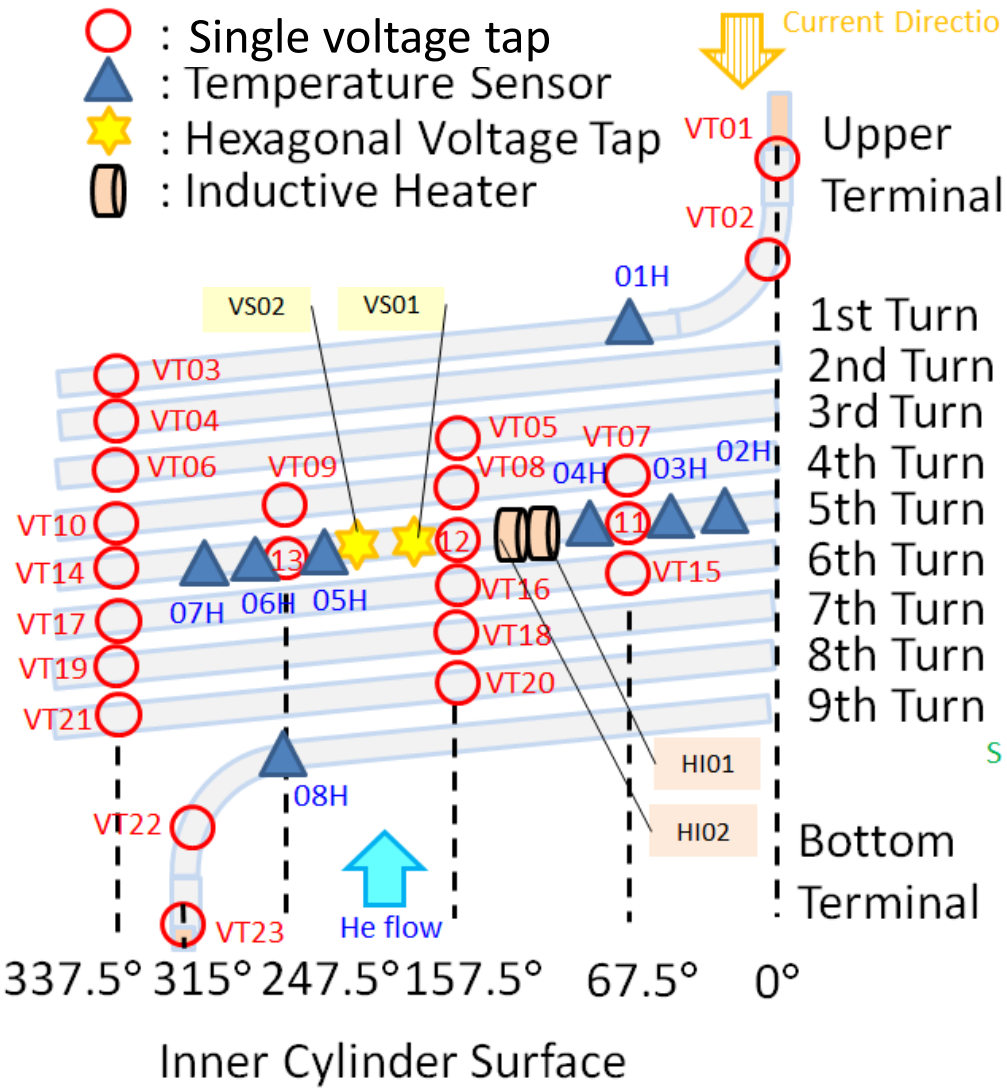


The first-in-the-world TF conductor performance test results with a coil configuration, <u>focused on T_{cs} measurement</u>, are presented.



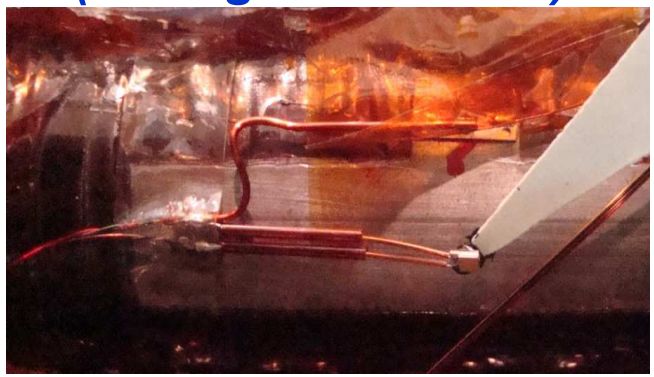
CS Model Coil

Instrumentation Map of TFIC



Voltage Taps
(below shows Hexagonal Tap)

Cernox on TF Conductor
(during installation)



Sample Preparation Condition

Two SULTAN Samples were also fabricated from the same TF conductor with the TFIC, and tested to compare the test result.

Prepared TF conductor	Prepared Test Samples	Heat Treatment Place
1 Conductor with strands fabricated by Bronze Route method	TF Insert Coil	TF Insert Coil Manufacturer Hitachi., Ltd.
	SULTAN Sample Left Leg	
	SULTAN Sample Right Leg	Swiss Plasma Center who owns SULTAN facility

The Specification of the Conductor cable

Item	Value or Detail
Strand Manufacturing Type	Bronze
I_c (12 T, 4.2 K) on ITER barrel	233.9 A
Cu/non-Cu ratio	0.954
Cr plating thickness	1.50 μm
RRR	240
Cable layout	((2sc+1Cu) × 3 × 5 × 5+(3 × 4Cu) × 6
Cable twist pitch of each cabling stage of 5stages	80, 142, 190, 302, 432 mm

Pattern for all samples:
250 hours at 570°C
and then
for 100 hours at 650°C

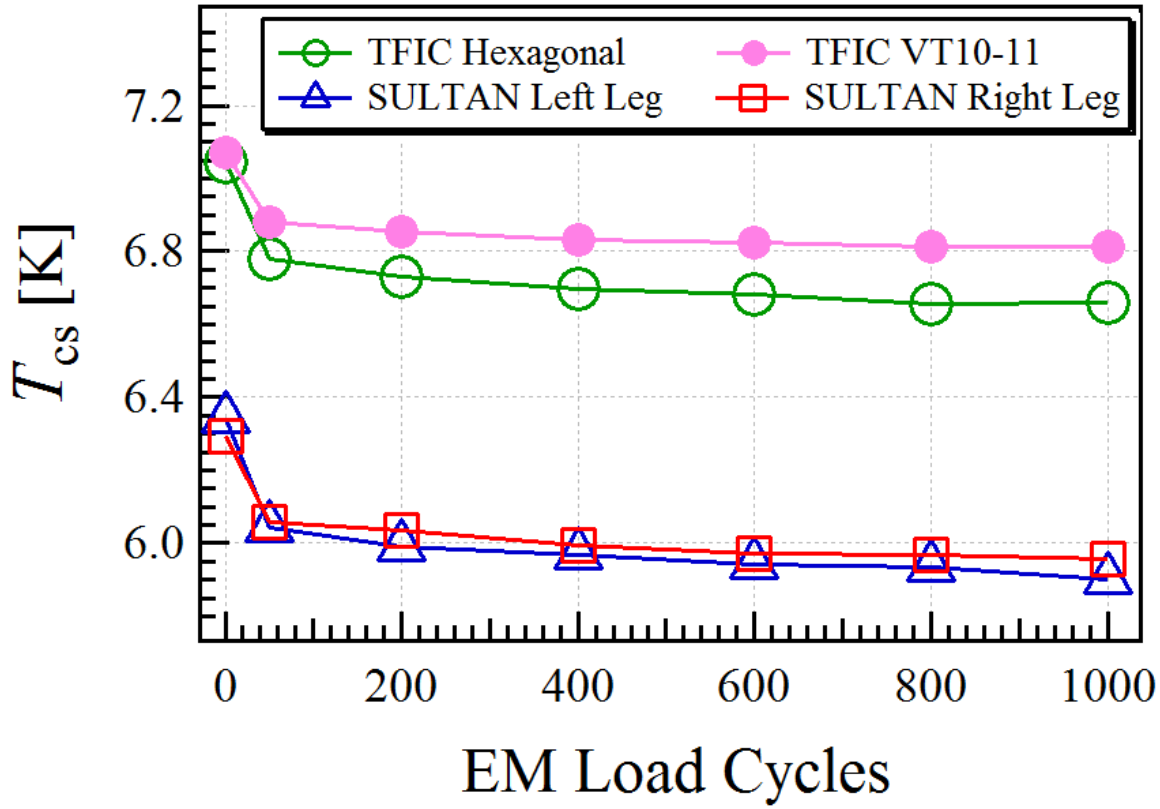
T_{cs} Measurement Sequence

Loading Sequence: the number of EM cycles, WUCD*s, and Quench* Test	TFIC T_{cs} meas. with 68 kA in 10.8T backup	SULTANs T_{cs} meas. with 68 kA in 10.8T backup
(After) 1 electromagnetic (EM) cycle	○	○
50 EM cycles	○	○
200~1000 EM cycles per 200 cycle, T_{cs} was measured	○	○
1st and 2nd WUCD	○	○
3rd WUCD	○	
2nd and 3rd Quench	○	
5th Quench then 4th WUCD	○	
5th WUCD	○	

*WUCD means the Warm Up to ~290 K and then Cool Down to 4 K.
*Quench was judged when the normal conduction voltage of the TFIC total length exceeded 100 mV.

3. Tcs Result

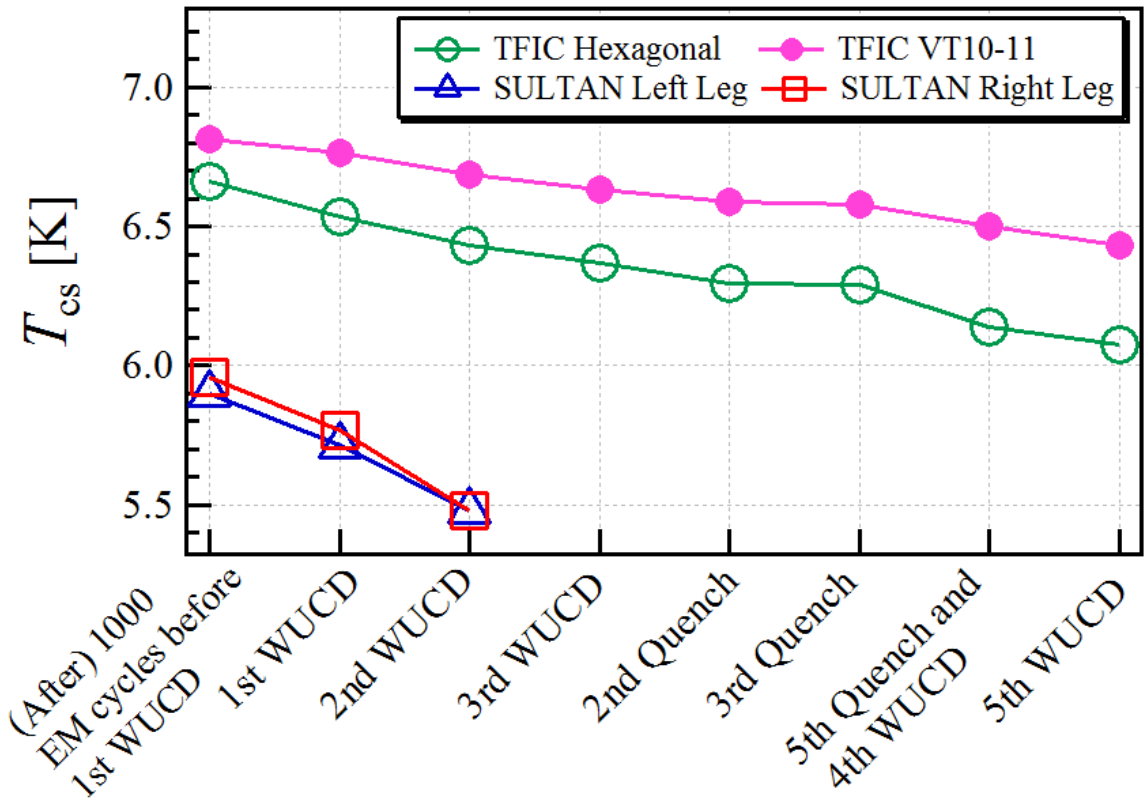
T_{cs} (68 kA, 10.8 T) before 1st WUCD



- Degradation of the T_{cs} of all samples occurred sharply during the first 50 EM cycles, and then, almost stopped during the 50 to 1,000 EM cycles.
- The T_{cs} value of the TFIC was higher than that of the SULTAN samples by around 0.7~0.8 K through the test duration till the 1,000 cycles.

3. Tcs Result

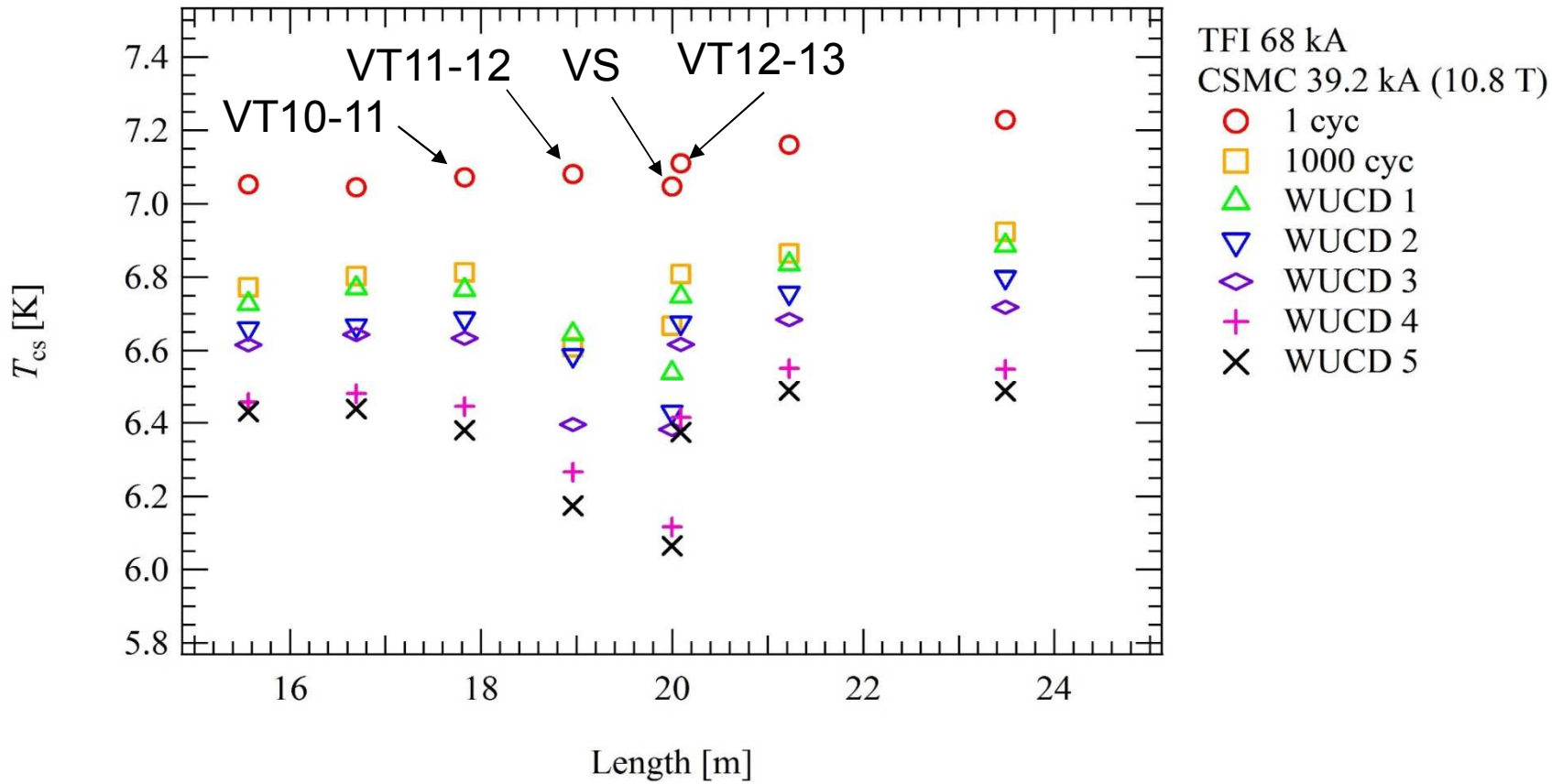
T_{cs} (68 kA, 10.8 T) After 1st WUCD



- T_{cs} degradation of the TFIC per WUCD cycle by 0.05 K to 0.13 K is smaller than 0.19 K to 0.29 K of that of SULTAN sample.
- For the TFIC, it was found that the T_{cs} degraded also after the quench tests. (At quench, the temperature of the TFIC cable rose up to more than 80 to 170 K.)

3. Tcs Result

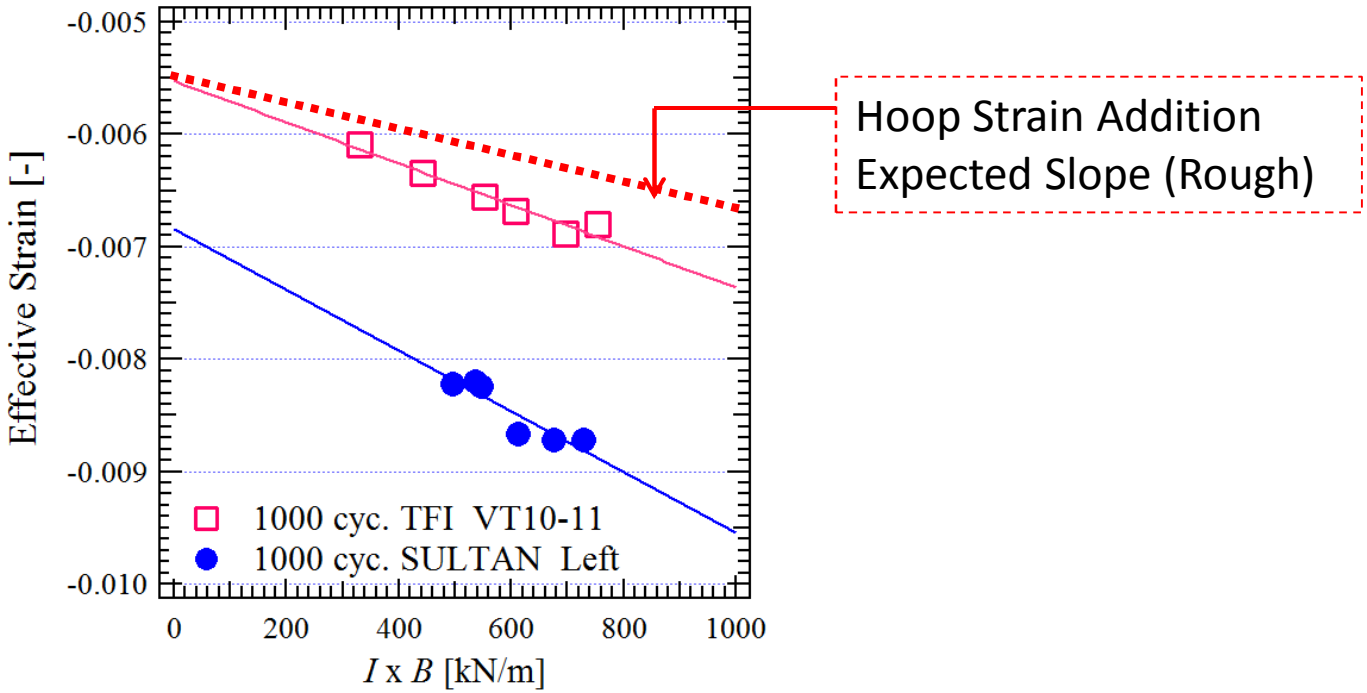
TFI T_{cs} (68 kA, 10.78 T) at Each Tap



- Only the inductive heater region (VT11-12) and hexagonal voltage tap region (VS) showed slight large T_{cs} drops compared with the adjacent voltage taps. At this point, the reason has not revealed yet.

3. Tcs Result

Effective Strain Evaluation



I: TFIC current
B: backup field on the TFIC

- ε_{eff} : effective strain, calculated by:

$$E(T) = \frac{E_0}{LA}\int_L\int_A \left(\frac{J_{op}}{J_c(B,T,\varepsilon_{eff})}\right)^n dz$$

E: electrical field [V/m], *A*: the cable area, *L:* distance of V-taps, E_0: 10μV/m, J_{op}: current per strand, *n*: *n*-value. Critical current characteristics of a strand $J_c(B, T, \varepsilon)$ was referred from [3]

- The difference of the effective strain of each sample kind is around 0.15%.
- Regarding the slope, which shows the dependency of the effective strain on the EM force, did not show much difference between the TFIC and the SULTAN samples.

⇒ Clear contribution from the hoop strain to the T_{cs} in the TFIC could not be seen.

[3] L. Bottura and Bernardo Bordini, "$J_c(B, T, \varepsilon)$ Parameterization for the ITER Nb_3Sn Production," *IEEE Trans. App. Supercond.*, vol. 19, No. 3, p1521-1524, Jun. 2009.

Conclusion

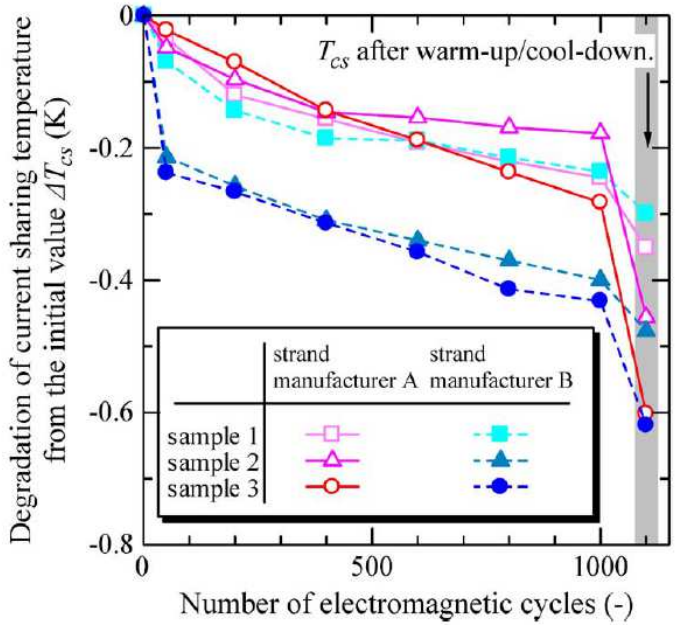
- The result of the T_{cs} measurement of the TFIC and SULTAN samples showed that the T_{cs} difference between the sample kinds was around 0.7~0.8 K, higher in TFIC, with a similar T_{cs} transition (till first WUCD).
- After the WUCD, the T_{cs} drop per WUCD was observed. The amount of the T_{cs} degradation of the TFIC per WUCD cycle by 0.05 K to 0.13 K was smaller than 0.19 K to 0.29 K of that of SULTAN sample.
- At some equipped points, the T_{cs} value showed slight large T_{cs} drops compared with the adjacent voltage taps. The reason is under investigation.
- From the result of the effective strain calculation per each EM load condition, it was difficult to see a clear contribution from the hoop strain to the T_{cs}. The reason is still not cleared.

Discussion about the TFIC results is keep going.

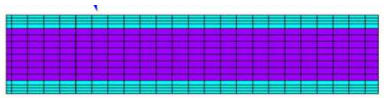
Supplementary

T_{cs} degradation in SULTAN

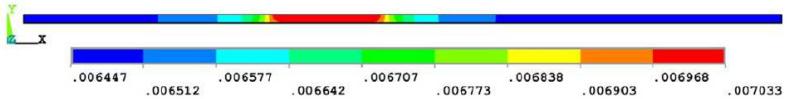
In SULTAN TF conductor test, large T_{cs} drop usually occurred after loadings (see left figure). One possible explanation of this cause is with the re-distribution of the thermal strain and cable sliding, caused by the sharp backup field gradient on the sample (see right figure).



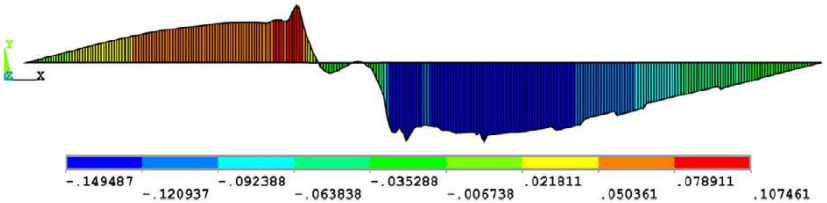
Degradation of T_{cs} from the initial against the number of electromagnetic (EM) cycles and WUCD (Warm Up & Cool Down) [2]



FEM Model of the TF conductor



Thermal strain distribution after EM loading, WUCD



Sliding amount of the cable in TF jacket

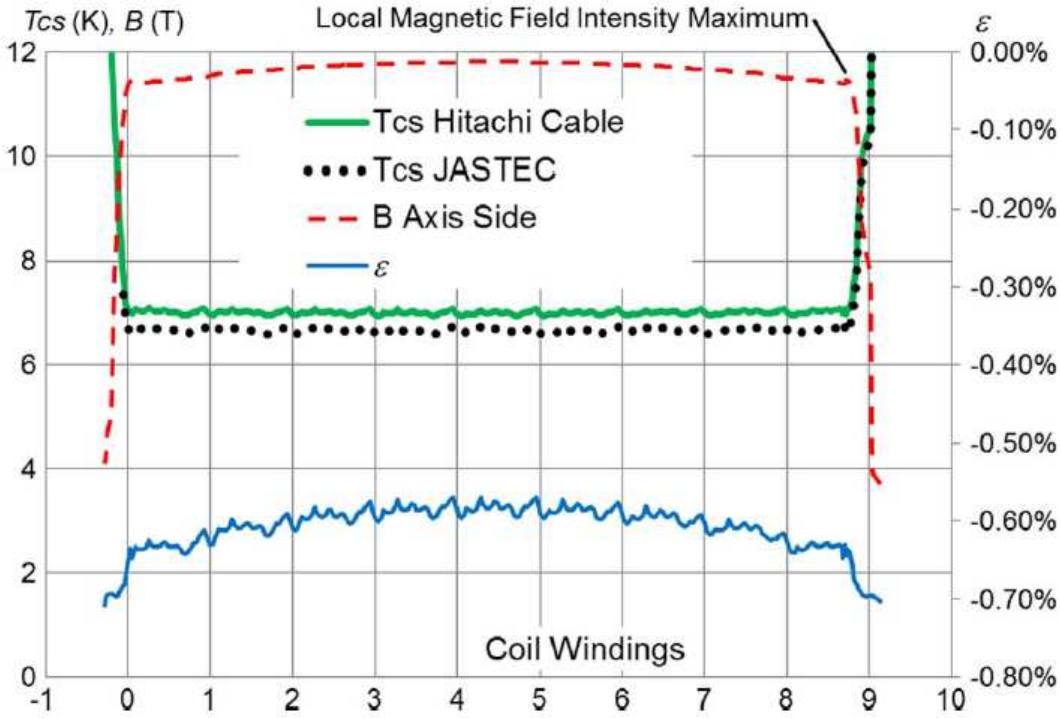
FEM model analysis of the thermal strain distribution and movement of the cable after EM loadings and WUCD [3].

[2] Y. Nabara *et al.*, "Examination of Japanese Mass-Produced Nb_3Sn Conductors for ITER Toroidal Field Coils," *IEEE Trans. App. Supercond.*, vol. 22, No. 3, #4804804, Jun. 2012.

[3] A. Devred *et al.*, "Strain redistribution effects on current-sharing measurements on straight samples of large Nb3Sn cable-in-conduit conductors," *Supercond. Sci. Technol.* 25 (2012) 054009.

TF Insert Test Condition

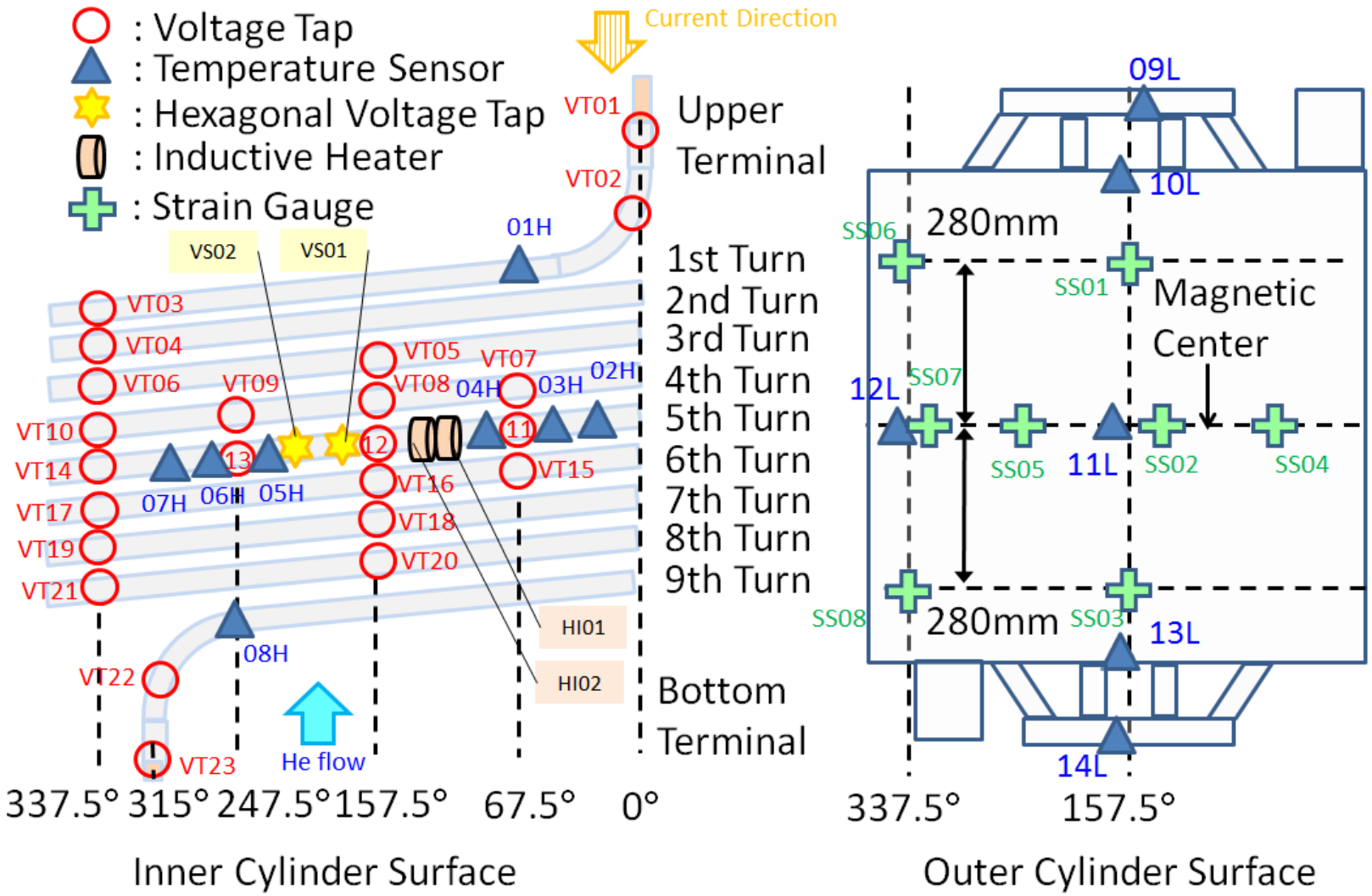
The test condition of the TFIC test is shown in the right.
The TF conductor in the TFIC was put in a magnetic field generated by the CSMC, which has a uniformity in a long length more than 35 m.



TF Insert test condition analysis [4]

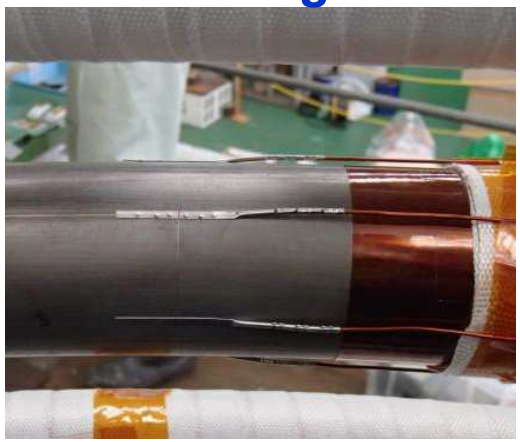
[4] A. Khodak, N. Martovetsky, A. Smirnov and P. Titus, "Analysis of TF Insert Coil," *IEEE Trans. App. Supercond.*, vol. 24, No. 3, #4201304, Jun. 2014.

Instrumentation Map

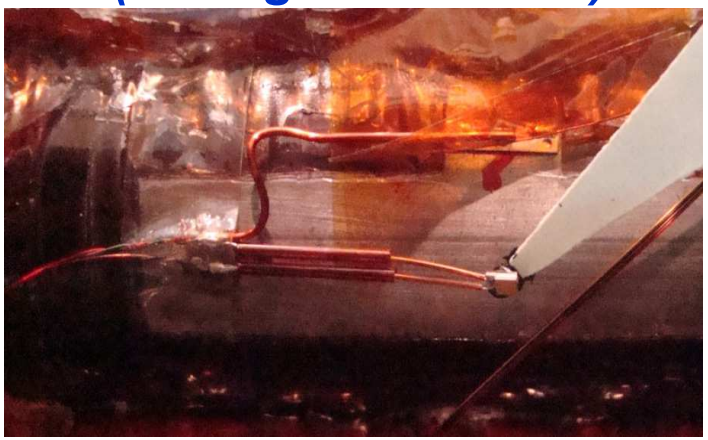


Instrumentations for TFI

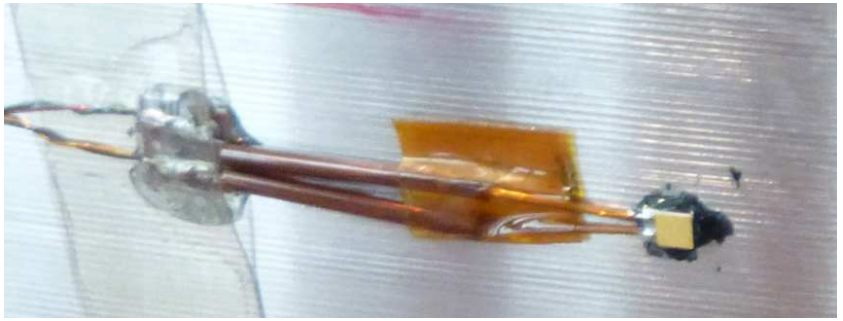
Voltage Taps
(below shows Hexagonal Volt. Tap)



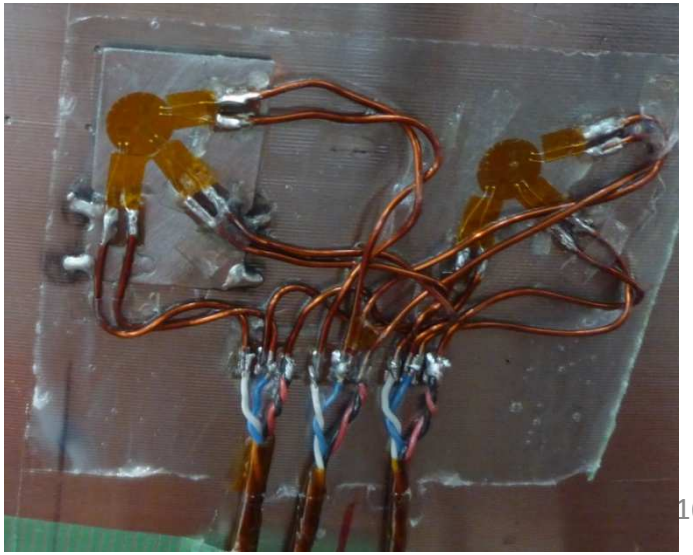
Cernox on TF Conductor
(during installation)



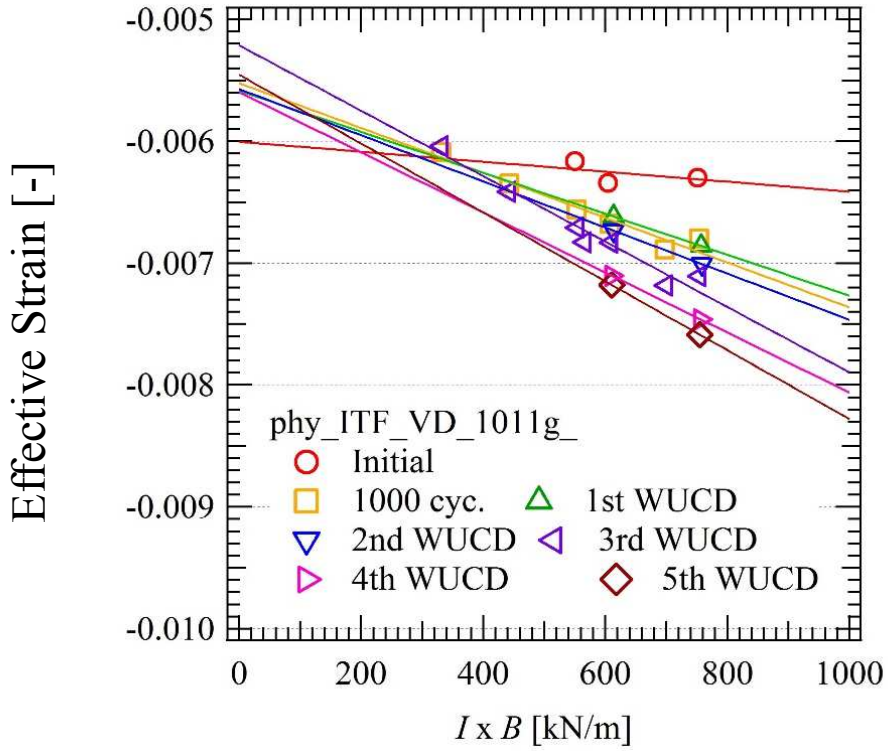
Cernox on Mandrel

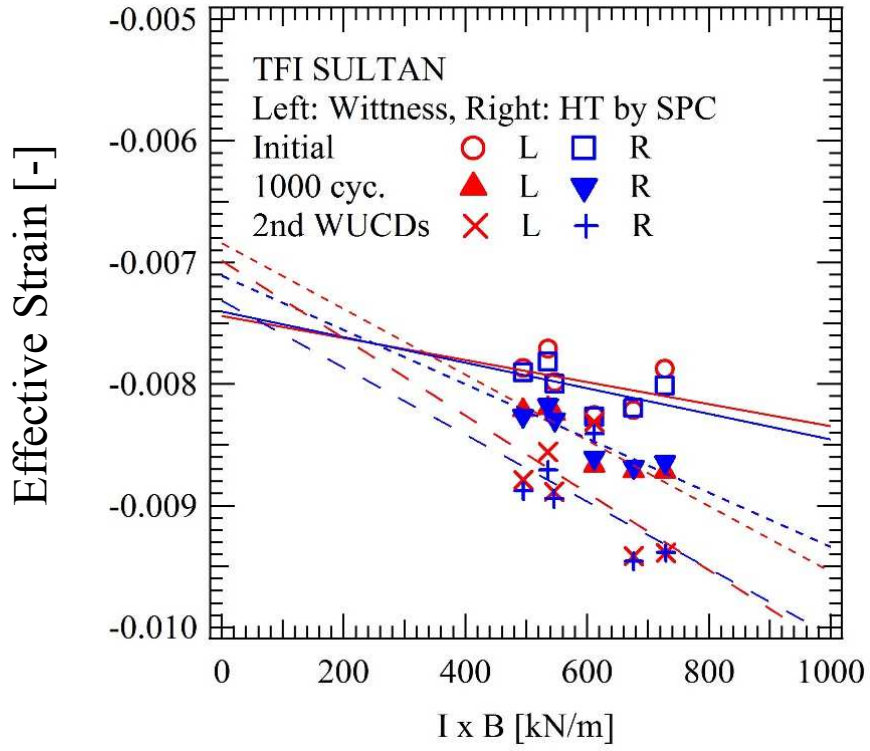


Strain Gauges on Mandrel

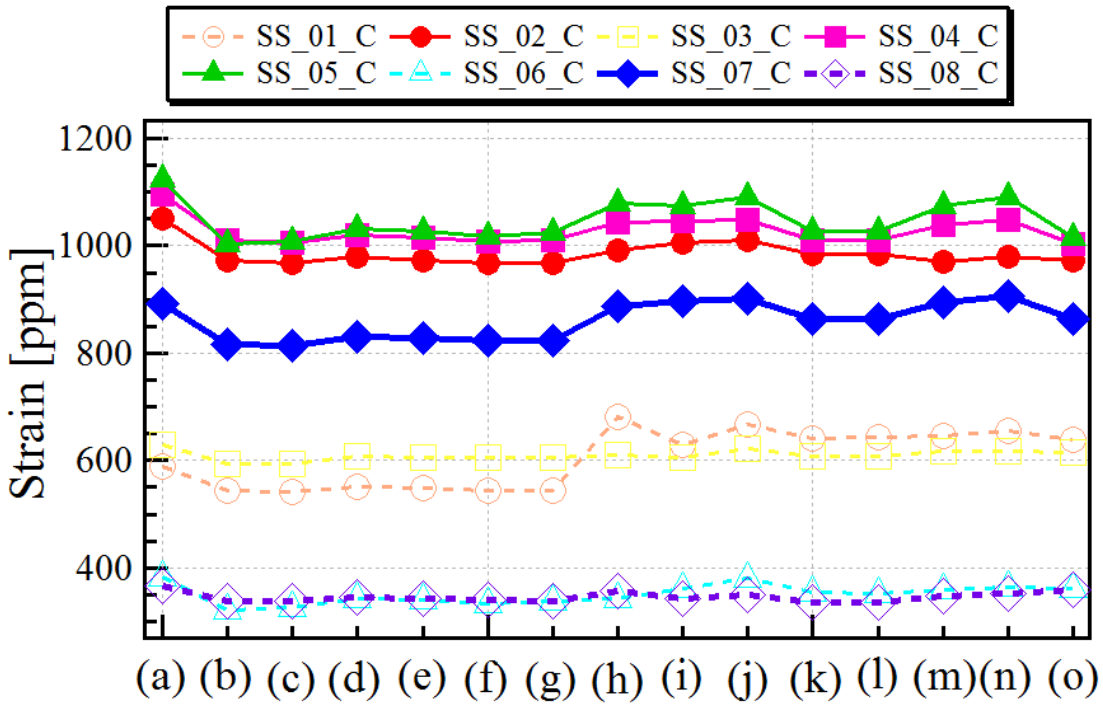


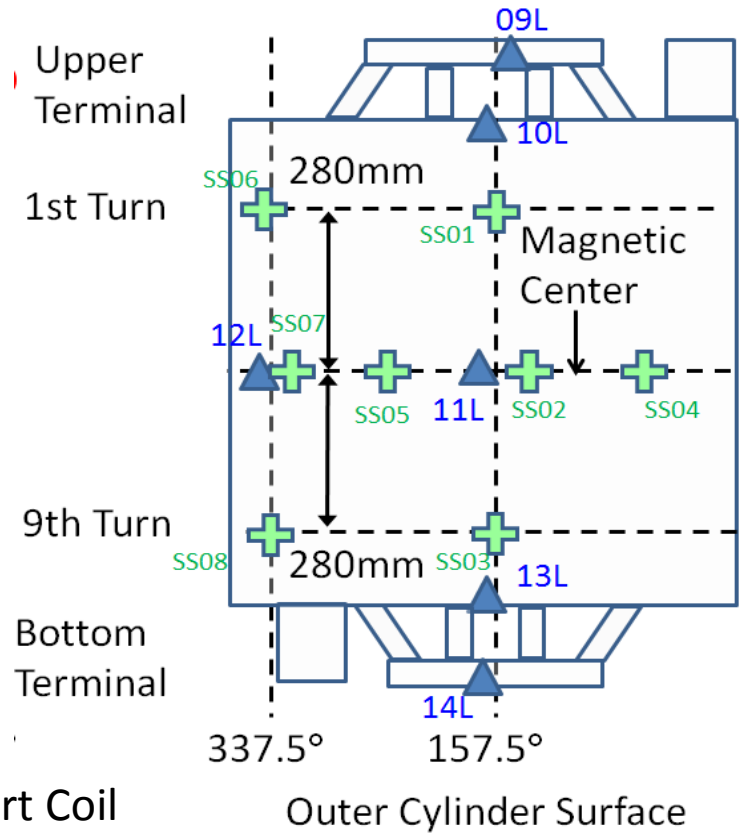
Effective Strain Evaluation





EM Load Peak Strain

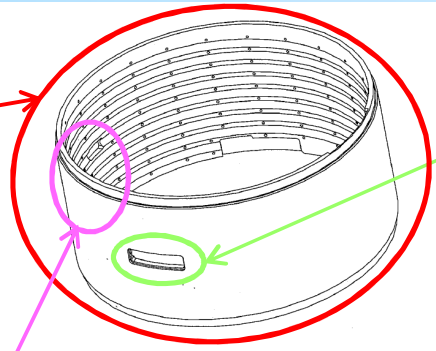




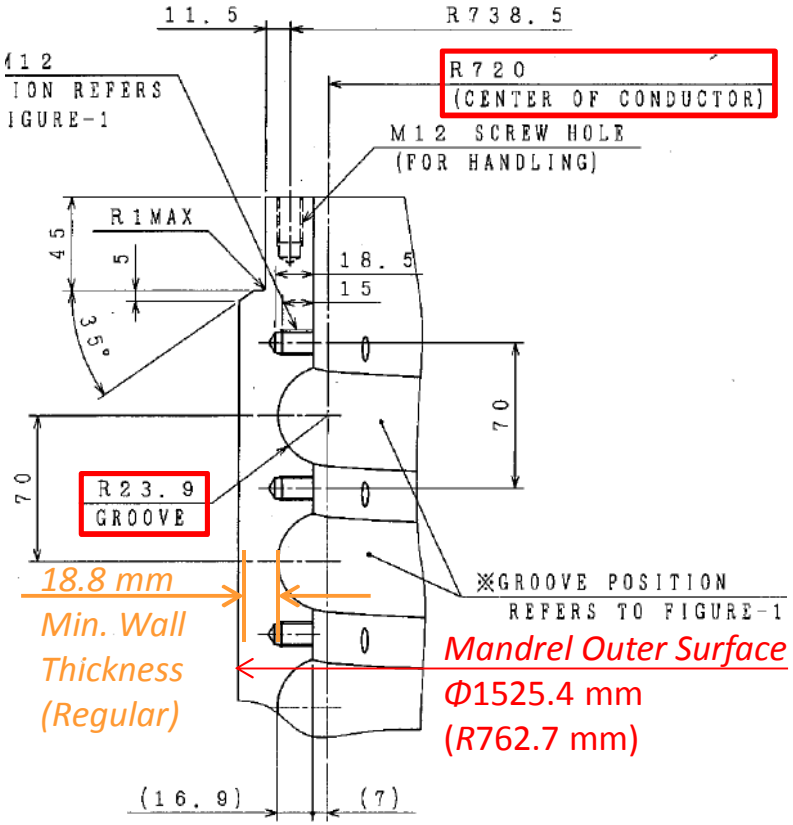
Circumferential strain measurement results of the TF Insert Coil mandrel during 68 kA application under a 10.8 T backup field.

Detail of the Mandrel Groove

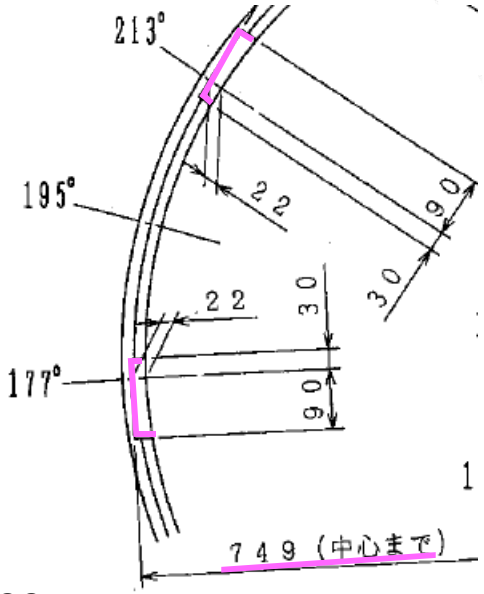
Regularly Arranged Part (Almost of All)

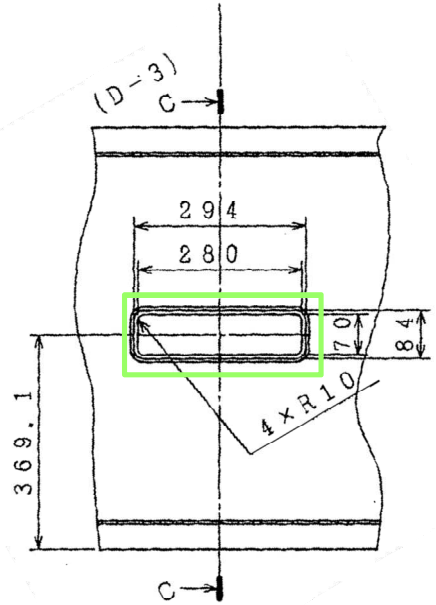


Window for IH coils installation



Grooves for Star voltage taps





※The vacant spaces at the grooves and the windows were filled with glass cloth and then impregnated

From Draw. No.310PB67-642 & 310PB67-509

T_{cs} per Element of Star Tap

T_{cs} was evaluated per element of star tap to confirm whether there are some tendencies or not. The result showed that the highest and the lowest voltage was seen at VS03 and VS05, respectively, only to find that clear tendency was not seen.