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

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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)

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

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

The first-in-the-world TF conductor performance test results with a coil configuration, focused on $T_{cs}$ measurement, are presented.
2. Sample Preparation

Instrumentation Map of TFIC

- Single voltage tap
- Temperature Sensor
- Hexagonal Voltage Tap
- Inductive Heater

Voltage Taps
(below shows Hexagonal Tap)

Cernox on TF Conductor
(during installation)
Two SULTAN Samples were also fabricated from the same TF conductor with the TFIC, and tested to compare the test result.

**Sample Preparation Condition**

**Prepared TF conductor**
- 1 Conductor with strands fabricated by Bronze Route method

**Prepared Test Samples**
- TF Insert Coil
- SULTAN Sample Left Leg
- SULTAN Sample Right Leg

**Heat Treatment Place**
- TF Insert Coil Manufacturer: Hitachi., Ltd.
- Swiss Plasma Center who owns SULTAN facility

**The Specification of the Conductor cable**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value or Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand Manufacturing Type</td>
<td>Bronze</td>
</tr>
<tr>
<td>$I_c$ (12 T, 4.2 K) on ITER barrel</td>
<td>233.9 A</td>
</tr>
<tr>
<td>Cu/non-Cu ratio</td>
<td>0.954</td>
</tr>
<tr>
<td>Cr plating thickness</td>
<td>1.50 $\mu$m</td>
</tr>
<tr>
<td>RRR</td>
<td>240</td>
</tr>
<tr>
<td>Cable layout</td>
<td>$(2sc+1Cu) \times 3 \times 5 \times 5 + (3 \times 4Cu) \times 6$</td>
</tr>
<tr>
<td>Cable twist pitch of each cabling stage of 5 stages</td>
<td>80, 142, 190, 302, 432 mm</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>(After) 1 electromagnetic (EM) cycle</th>
<th>TFIC $T_{cs}$ meas. with 68 kA in 10.8T backup</th>
<th>SULTANs $T_{cs}$ meas. with 68 kA in 10.8T backup</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 EM cycles</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>200~1000 EM cycles per 200 cycle, $T_{cs}$ was measured</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>1st and 2nd WUCD</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>3rd WUCD</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>2nd and 3rd Quench</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>5th Quench then 4th WUCD</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>5th WUCD</td>
<td>○</td>
<td></td>
</tr>
</tbody>
</table>

*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.
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 1$^{st}$ 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.)
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

- \( \varepsilon_{\text{eff}} \): effective strain, calculated by:
  \[
  E(T) = \frac{E_0}{L A} \int_A \left( \frac{J_{\text{op}}}{J_c(B, T, \varepsilon_{\text{eff}})} \right)^n \, dz
  \]

- 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.
  \[ \Rightarrow \text{Clear contribution from the hoop strain to the } T'_{\text{cs}} \text{ in the TFIC could not be seen.} \]

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
1. Introduction

$T_{cs}$ 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].


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]

2. Sample Preparation

Instrumentation Map

- Voltage Tap
- Temperature Sensor
- Hexagonal Voltage Tap
- Inductive Heater
- Strain Gauge

Current Direction

Upper Terminal
1st Turn
2nd Turn
3rd Turn
4th Turn
5th Turn
6th Turn
7th Turn
8th Turn
9th Turn

Bottom Terminal

337.5° 315° 247.5° 157.5° 67.5° 0°

Inner Cylinder Surface

280mm

337.5° 157.5°

Outer Cylinder Surface

280mm

09L 10L 12L

SS06 SS01 SS02

SS05 SS03 SS04

SS08
2. Sample Preparation

**Instrumentations for TFI**

- **Voltage Taps**
  (below shows Hexagonal Volt. Tap)

- **Cernox on Mandrel**

- **Cernox on TF Conductor**
  (during installation)

- **Strain Gauges on Mandrel**
Effective Strain Evaluation

3. Tcs Result

![Graph showing effective strain evaluation](image-url)
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)

Mandrel Outer Surface Φ1525.4 mm (R762.7 mm)

18.8 mm Min. Wall Thickness (Regular)

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.
$T_{cs}$ 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.