Design of Superconducting Coil System
for remodeling JT-60 (JT-60SC)

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JAERI

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Configuration of JT - 60SC Coil System

Main parameters of the TF coil

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Height / Width</td>
<td>6.0 m / 3.7 m</td>
</tr>
<tr>
<td>Number of Coils</td>
<td>18</td>
</tr>
<tr>
<td>Max. Magnetic Field</td>
<td>7.4 T</td>
</tr>
<tr>
<td>Total Stored Energy</td>
<td>1.7 GJ</td>
</tr>
<tr>
<td>Centering Force per Coil</td>
<td>33.6 MN</td>
</tr>
<tr>
<td>Weight per Coil</td>
<td>23.5 ton</td>
</tr>
</tbody>
</table>

Main parameters of the CS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of Winding</td>
<td>5.4 m</td>
</tr>
<tr>
<td>Inner Diameter of Winding</td>
<td>1.6 m</td>
</tr>
<tr>
<td>Outer Diameter of Winding</td>
<td>2.1 m</td>
</tr>
<tr>
<td>Number of Coils</td>
<td>4</td>
</tr>
<tr>
<td>Max. Magnetic Field</td>
<td>7.4 T</td>
</tr>
</tbody>
</table>

Main parameters of the EF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Coils</td>
<td>6</td>
</tr>
<tr>
<td>Max. Diameter of Winding</td>
<td>10.6 m</td>
</tr>
<tr>
<td>Max. Magnetic Field</td>
<td>5 T</td>
</tr>
</tbody>
</table>

Total weight: 2000 tons
Winding Configuration of TF coil and CS

TF coil

Central Solenoid

7DP
154 turns

23DP
414 turns
Selection of Superconductor for TF Coil

NbTi, Nb$_3$Sn and Nb$_3$Al strands compared in Jc performance with stainless steel conduit.

$B=7.4T$  $\varepsilon=\pm 0.7\%$

- Nb$_3$Sn: 650A/mm$^2$ at 4.2 K, 12 T, 0.25% strain
- Nb$_3$Al: 600A/mm$^2$ at 4.2 K, 12 T, 0% strain
Development of Nb$_3$Al conductor ( II )

30m length full size conductor fabrication

- Cable fabrication: use of a 11 km Nb$_3$Al strand and a capper wire
  - Pattern: $3 \times 3 \times 3 \times 3 \times 4 = 324$
  - Final stage twist pitch = 350 mm

- Conduit fabrication
  - Material: 316 LN
  - Shape: Square conduit with a circular hole
  - Unit length: 10m (Hot extrusion and cold work)
  - 30 m conduit: 2 butt weldings with 3 unit conduits

- Conductor fabrication
  - Cable was inserted into the 30 m length conduit and then it was drawn down to the nominal size

A 30 m Nb$_3$Al full size conductor was completed
AC Loss Reduction Technique for the conductor of CS (I)

Conductor for CS and EF 4 coil requires low coupling loss of 50 ms level.

Dependence of coil operation frequency on coupling loss was measured in ITER - CSMC test.

To break the sintering at room temperature, the application of bending strain to a full size conductor sample was tried and ac loss was measured.

This shows that the sintering between strands is broken by electro-magnetic force during coil operation and ac loss is decreased because the resistance between strands is inc eased.
Joint Structure

Operation Condition

- Max. Transport Current : 20 kA
- Max. Magnetic Field : 4.8 T
- Max. Changing Field Rate : 2.0 T/s
- Operating life : 10 years
- Fatigue life : 18000 times

Requirements

- Resistance : < 7nΩ
- Time constant of coupling current : < 1s
- Temperature margin : < 1K

To realize these high endurance and low ac loss the following joint structure is designed.

Design

- Lap type
- Use of Ag brazing for contact between cable and Cu pipe
- Cable void fraction of 25 %
The Need of JT-60 remodeling with superconducting coil

Investigation of plasma performance in the region beyond the diffusion time of plasma current at the break-even level.

Long Pulse Operation

Use of Superconducting Coil

PRINCIPAL PARAMETERS OF JT-60SC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Current</td>
<td>4 MA</td>
</tr>
<tr>
<td>Flat Top Plasma Current</td>
<td>100 s</td>
</tr>
<tr>
<td>Plasma Major Radius</td>
<td>2.8 m</td>
</tr>
<tr>
<td>Plasma Minor Radius (maximum)</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Plasma Elongation</td>
<td>1.8</td>
</tr>
<tr>
<td>Triangularity</td>
<td>0.35</td>
</tr>
<tr>
<td>Divertor Configuration</td>
<td>Single Null</td>
</tr>
<tr>
<td>Toroidal Field at the Major Radius</td>
<td>3.8 T</td>
</tr>
</tbody>
</table>
Size of the JT-60SC Superconducting Coil

TF Coil
(Steady operation)

CS and EF Coil
(Pulsed operation)

Magnet Stored Energy (GJ)

Maximum Magnetic Field (T)

0.1

1

10

100

0.4

1

10

BS (T·m²)

0.4

0.2

0.4

1

2

4

10

20

40

ITER-TF

JT60SC-TF

LHD-II

Tore-supra

CSMC

LCT

CSMC

CSI

DPC-EX

JT-60SC-CS

US-DPC

pulser C

(JAERI)

B : Peak field
S : Inner dia. area

1.5 kJ coil

(ANL)

Operated

Constructing, design

Trium-1M

MFTF

LHD-I

TMC

ATLAS

Operated

Design

M010911d_T.A
# Conductors for TF coil, CS and EF coil

<table>
<thead>
<tr>
<th>Structure</th>
<th>316 LN</th>
<th>Superconducting Strand</th>
<th>Pure copper wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al (or Nb)</td>
<td>324</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.74 mm</td>
<td>36 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>324</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.78 mm</td>
<td>36 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NbTi</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.70 mm</td>
<td>36 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Max. Magnetic Field | 7.4 T | 7.4 T | 5 T |
| Nominal Current    | 19.4 kA | 20 kA | 20 kA |
| Operating Temp     |        |        |
| SC Material        | 316 LN | 316 LN | 316 LN |
| Coating Material   |        |        |
| No. of Total Strands |        |        |
| No. of SC Strands  |        |        |
| No. of Cu Wires    |        |        |
| Cu/non Cu Ratio    |        |        |
| Strand Diameter    |        |        |
| Void Fraction      |        |        |
| Weight of SC strand|        |        |

M010903a_T.A
Development of Nb$_3$Al conductor (I)

Nb$_3$Al strand development

- Strand diameter: 0.74 mm
- Cu non Cu ratio: 4
- Filamentary diameter: 55 $\mu$m
- $J_c$ at 12 T and 4.2 K: 600 A/mm$^2$
- $n$ value: 45

High quality jelly - roll preparation

A Nb$_3$Al strand of 11 km length was successfully fabricated with no breakage
Using the 30 m length full size Nb$_3$Al conductor the following R &Ds are planned:

1. A two turns coil is fabricated and tested
   - Verification test of React and Wind technique
     Application of same strain as a real TF coil conductor to a two turns coil conductor

2. Short Sample test
   - Conductor performance measurement
     \( I_c - B - T \)
     AC loss
   - Joint performance measurement
     \( I_c - B - T \)
     Joule loss
     AC loss
AC Loss Reduction Technique for conductor of CS (II)

Method to apply 0.2% strain to the conductors of CS.

\[ \varepsilon_t = \frac{W \cdot d}{\pi D^2} \]

0.2% strain is applied to conductors due to expanding the space between the pancakes after heat treatment of the double pancakes. At that time, turn insulation work is carried out.

0.2% strain is within the region of elastic on the stress-strain curve of a CIC conductor.

![Stress-Strain Curve](Specking_FZK.png)
The Design of JT-60 remodeling with a superconducting system has been carried out with new technologies to perform the extensive plasma experiment. The features of this system are as follows:

1. The TF coil has a magnetic stored energy of 1.7 GJ that is the largest in superconducting coil constructed so far.

2. High copper ratio strands (4 for Nb$_3$Al and 2.3 for Nb$_3$Sn) were developed to realize high current density in winding and coil fabrication with low cost.

3. A Nb$_3$Al cable-in-conduit conductor with s.s.conduit is considered to be applied to the TF coil, which enable it to make with a react-and-winding technique.

4. In order to decrease inter strand coupling loss in CS conductor, a bending strain technique was considered.

5. Joints between pancakes use brazing between cable and copper tube to get strongly mechanical contact.