The ITER Magnet Systems: Progress on Construction


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7) Institute for Plasma Physics, Chinese Domestic Agency (CN), Hefei, China
Outline

1. ITER Magnet Systems: Procurement Arrangements and Schedule

2. Cable-in-Conduit Conductors Design and Manufacture

3. Toroidal Field (TF) Coils

4. Central Solenoid (CS) Coils

5. Poloidal Field (PF) Coils

6. Correction Coils (CC), Magnet Supports and Coil Feeders

7. Summary
ITER Magnet Systems

48 Superconducting Coils:
- 18 TF coils
- 6 CS modules
- 6 PF coils
- 9 pairs of CC
- Feeders

<table>
<thead>
<tr>
<th>System</th>
<th>Energy GJ</th>
<th>Peak Field T</th>
<th>Total MAT</th>
<th>Cond length km</th>
<th>Total weight t</th>
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<tbody>
<tr>
<td>Toroidal Field TF</td>
<td>41</td>
<td>11.8</td>
<td>164</td>
<td>82.2</td>
<td>6540</td>
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<tr>
<td>Central Solenoid</td>
<td>6.4</td>
<td>13.0</td>
<td>147</td>
<td>35.6</td>
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<td>Poloidal Field PF</td>
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<td>6.0</td>
<td>58.2</td>
<td>61.4</td>
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<tr>
<td>Correction Coils CC</td>
<td>-</td>
<td>4.2</td>
<td>3.6</td>
<td>8.2</td>
<td>85</td>
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</table>

(for comparison → 10.5 GJ magnetic energy in the 27 km tunnel of the Large Hadron Collider at CERN)
## Complex Sharing between Domestic Agencies

<table>
<thead>
<tr>
<th>Component</th>
<th>IO</th>
<th>CN</th>
<th>EU</th>
<th>KO</th>
<th>JA</th>
<th>RF</th>
<th>US</th>
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<tbody>
<tr>
<td>TF Conductors</td>
<td>7%</td>
<td>20%</td>
<td>20%</td>
<td>25%</td>
<td>20%</td>
<td>8%</td>
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<tr>
<td>TF Windings + Insertion</td>
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<td>10 coils</td>
<td>9 coils</td>
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<td></td>
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<td></td>
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<td>TF Case Sections</td>
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<tr>
<td>Pre-compression Rings</td>
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<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>TF Gravity Supports</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>CS Conductors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>CS Coils + Structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>PF Conductors</td>
<td>65%</td>
<td>21%</td>
<td></td>
<td></td>
<td></td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>PF Coils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 coils</td>
</tr>
<tr>
<td>PF Supports</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC Conductors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC + Supports</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18 coils</td>
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<td>Magnet Feeders</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Instrumentation</td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

18 Procurement Arrangements signed up to now, last 2 to be signed by 2010
Complex Sharing of TF Coils

Courtesy of A. Maas, ITER

23rd IAEA-FEC, Daejeon (Korea), 13 October 2010
Another Challenge: the ITER Schedule

- 2 years qualification programme with the manufacture of mock-ups and dummy windings
- Delivery of the first conductors in 2010
- Start of installation of the first PF and TF coils in 2015
- Completion of the deliveries with the last PF coil and CS coils in 2017

→ A true managerial and technological challenge ...
All four magnet systems (TF, CS, PF and CC) are using the same concept
Strand type (NbTi or Nb$_3$Sn) defined by max. field
Number of strands defined by nominal current
Outer conduit material and shape (round, square) defined by magnet design
Production started in 2008 (strand, cabling & jacketing)
Conductor Manufacture

1st Stage
- Conductor Manufacture
- Strand
- Cu Wire

2nd Stage
- Sub-Wrap
- Cu Wire
- Cable

3rd Stage
- 2nd Stage
- 4th Stage
- Cu Core Cable
- Cu Sub-Cable

4th Stage
- Wrap
- Central Spiral
- Jacket Assy
- Jacket
Strand Production: Status

• More than **1,600 billets** (100 tons, all TF strand) registered in Database

→ Stepping up to 100 tons/year, an increase of two orders of magnitude from previous Nb$_3$Sn worldwide production rate

• Most material from JA, followed by KO, RF, EU and US:

- Majority of billets “in work”, but being released
Cabling & Jacketing

- Final cable covered by steel wrap
- After final wrap, cable ready for insertion and compaction into jacket

Final stage (5th) cabling around central spiral

- Welding and inspection of circular and square extruded tubes

Several thousands of stainless steel tubes to be produced and welds to be made and inspected …
Jacketing Facilities

TF & CS Facility in JA

Jacketing Equipment in RF

TF & PF Facility in CN

First JA full length dummy conductor completed in 2010

\[ \text{cfr. ITR/P1-50: Takahashi, Y., et al.,} \]

\"Technology Development for the Manufacture of Nb₃Sn Conductors for ITER Toroidal Field Coils\", JAERI Naka, Japan

• KO might use JA jacketing facility

• EU and US facilities construction to be started soon
## Toroidal Field Coils

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of coils</td>
<td>19</td>
</tr>
<tr>
<td>Total stored energy (GJ)</td>
<td>~41</td>
</tr>
<tr>
<td>Max. conductor field (T)</td>
<td>11.8</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>Operating current (kA)</td>
<td>68</td>
</tr>
<tr>
<td>Operating temperature (K)</td>
<td>5</td>
</tr>
<tr>
<td>Number of turns</td>
<td>134</td>
</tr>
<tr>
<td>Height (m)</td>
<td>12.6</td>
</tr>
<tr>
<td>Weight (t)</td>
<td>~310</td>
</tr>
<tr>
<td>Centering force per coil (MN)</td>
<td>~400</td>
</tr>
<tr>
<td>Discharge time constant (s)</td>
<td>11</td>
</tr>
<tr>
<td>Max. voltage (kV)</td>
<td>7</td>
</tr>
</tbody>
</table>

**Design validation through**

**TF Model Coil tested in 2001**
Wind, React and Transfer

- The TF coils are made using W,R&T technique. The complex manufacturing technique, together with the large dimensions, makes the TF coil a huge technological challenge.

  ➔ Major issue is the permanent deformation of the superconductor winding during heat treatment, which makes complex the transfer into radial plates.

  **Note:** up to 10 conductor supplies with different behaviour.

- **EU** has chosen a multiple split procurement between radial plates, coil windings and insertion in the cases.
  ➔ Contract for winding manufacture awarded to Iberdrola/ASG/Elytt in July 2010.

- **JA** to use one prime contractor, Toshiba, at least for the first two years of preparation phase, with the manufacture of prototypes of coil winding, radial plates and cases.

  ![1/3 scale winding table for TF coil prototype (JA)](image)

  **Qualification of proposed irradiation resistant resin system with epoxy/cyanate ester blend completed:**
The challenge of transfer of reacted conductor inside the TF radial plates

Nominal 605 +/- 11

Open TF coil
double pancake

Umbrella structure

Heat treatment support

Support platform

Radial plate
(under the support)

Radial plate articulated support
Manufacture of Radial Plate Prototypes (EU)

Forging of radial plate segment (CNIM)

Machined side radial plate segment (CNIM)

Radial plate segment produced by powder HIPping (SIMIC)

Local vacuum Electro Beam Welding machine (CNIM)

Assembly of radial plate with GTAW welding (in progress at SIMIC)

23rd IAEA-FEC, Daejeon (Korea), 13 October 2010
Prototype of side plate for TF coil case under forging process (above) and finished shape (below)
### Central Solenoid Coils

**Number of modules**: 7

**Total stored energy (GJ)**: ~6.4

**Max. conductor field (T)**: 13

**Superconductor**: Nb$_3$Sn

**Operating current (kA)**: 45

**Operating temperature (K)**: 5

**Turns per module**: 535

**Total weight of coil assembly (t)**: ~980

**Max. voltage to ground (kV)**: 20

**CS stack composed of 6 independently powered modules wound in hexa-pancakes**

- **Detailed design phase in progress after PA signature**
- **Design validation through CS Model Coil tested in 2000, but new CS Insert required to confirm conductor performances under tensile hoop load conditions**
Poloidal Field Coils

6 PF coils independently powered, wound in double pancakes

- Confine and shape the plasma
- PF1 & PF6 control plasma vertical displacement
- Conductor field limited to 6.5 T → NbTi, three grades of conductors depending on max. field
- Coils are large (24 m diameter) but use of NbTi simplifies construction

Design validation through PF Insert Coil tested in 2008
PF Coil Fabrication

Proposed winding scheme by EU DA: call-for-tender for manufacture of PF2-PF6 is in progress, supply contract to be placed in early 2011

Winding tooling prepared by RF DA for PF1 double pancakes: insulating and impregnation equipment & devices have been designed and procurement is in progress.
PF Coil On-site Manufacturing Building

(Full occupation of building not realistic)
Correction Coils & Magnet Supports (CN)

• **Correction Coils**: detailed design and analysis activity complete, qualification of winding/insulation equipment and coil case manufacture/welding in progress, manufacture of dummy conductor complete
  ➔ cfr. *ITR/P1-52: Wei, J., et al., “R&D of the ITER Correction Coil Magnet System”, Institute of Plasma Physics, Hefei, China*

• **PF Coil Clamps and Gravity Supports**: detailed design and analysis complete, qualification of manufacturing techniques started
  ➔ cfr. *ITR/P1-45: Lee, P.J., et al., “R&D of the Fabrication Technology for ITER Magnet Supports”, Southwestern Institute of Physics, Chengdu, China*

• **Magnet Feeders and Current Leads**: detailed design of in-cryostat feeders and outer terminal boxes under final review, R&D on critical components started
Summary

- **Conductors**: ~100 tons of strand already manufactured; mass production of superconducting strand established; most of manufacturing lines and production facilities in 6 ITER Members either ready or almost complete.

- **TF Coils**: First qualification stage of the TF coil manufacture started; full scale mock-ups of radial plates and windings being manufactured.

- **CS Coils**: Detailed design of the coils and their support structure in progress, especially for some critical items like joints and terminations; start up of several qualification and preparation activities has taken place.

- **PF Coils**: Manufacturing equipment already been prepared for PF1; supply contract for the EU coils to be placed in early 2011.

- Manufacture of the Correction Coils and the TF/PF supports starting; design of the Magnet Feeders still needs to be finalized due to the complicated interfaces.

➤ **Note**: Very tight delivery schedules the six DAs have to work with, while solving impressive challenges on components, whose technical complexity and size have not been exploited before, and (least but not last) meeting the required quality standards.