The ITER Magnets at MATEFU

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Structure of Presentation

Design Overview
  TF coils PF coils CS coils Correction coils Feeders
  Conductor
  Cooling
  Forces

Design Focus 2007-9
  Tolerancing of magnet system

Procurement Arrangements
  How ITER is procured
  Status

Procurement and Qualification Status
## Overall Features

### 4 Main Systems, all superconducting

<table>
<thead>
<tr>
<th>System</th>
<th>Energy GJ</th>
<th>Peak Field</th>
<th>Total MAT</th>
<th>Cond length km</th>
<th>Total weight t</th>
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</thead>
<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>
<td>974</td>
</tr>
<tr>
<td>Poloidal Field PF</td>
<td>4</td>
<td>6.0</td>
<td>58.2</td>
<td>61.4</td>
<td>2163</td>
</tr>
<tr>
<td>Correction Coils CC</td>
<td>-</td>
<td>4.2</td>
<td>3.6</td>
<td>8.2</td>
<td>85</td>
</tr>
</tbody>
</table>
# FUNCTIONALITY

<table>
<thead>
<tr>
<th>TF</th>
<th>18 coils</th>
<th>Field to confine charged particles in the plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>6 coils</td>
<td>Inductive flux to ramp up/drive plasma</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasma shaping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasma vertical stability</td>
</tr>
<tr>
<td>PF</td>
<td>6 coils</td>
<td>Radial position equilibrium of plasma</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasma shaping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasma vertical stability</td>
</tr>
<tr>
<td>CC</td>
<td>18 coils</td>
<td>Correction of error field harmonics</td>
</tr>
</tbody>
</table>
The ITER magnet system is made up of:

- 18 Toroidal Field (TF) Coils,
- a 6-module Central Solenoid (CS),
- 6 Poloidal Field (TF) Coils,
- 9 pairs of Correction Coils (CC).

ITER Magnet System

Pair of TF Coils

CS Coil

PF & CC Coils
• Magnet Feeders include
  − Containment ducts,
  − NbTi CICC busbars,
  − Supplies (instrumentation, He lines)
  − expansion boxes and terminal boxes
  − Ag-Au(5.4%) BiSCCO 2223 HTS current leads.

Detail of CC Coil Feeder

ITER Feeder System

68 kA HTS Prototype
Lead Developed by FZK
Plasma magnetic control:

1) plasma initiation
2) control of plasma current
3) control of positions and shape (six plasma-wall gaps). Slow feedback loop is used, timescale of 5-10 s.
4) Vertical stability control. Fast feedback loop is used, timescale <1 s with P2-P5 and possibly CS2U,L

The plasma position is controlled at the points g1-g6 to keep the first wall and diverter heat loads to acceptable values.
ITER Project Site Layout: 3-D graphics view

Bird's-eye view of ITER site
Draft: 02.03.09

1. Tokamak building
2. Tokamak complex evacuation support structure
3. Assembly building
4. Spallation building
5. HTS Magnet building
6. Cryomodule building
7. Hot cell building
8. Radioactive waste building
9. Tokamak power supply control building
10. Magnet power conversion building I
11. Magnet power conversion building II
12. EPL power supply building
13. Plate power high voltage rectification area
14. Multi-solenoid current distribution building
15. HPL high voltage power supply building
16. Fast reactor power control building
17. Reactor power converter area
18. Reactor power high voltage rectification area
19. Reactor storage tank
20. Emergency power supply building (IPL-1)
21. Emergency power supply building (IPL-2)
22. Emergency power supply building (IPL-3)
23. Marine equipment distribution building (MCD)
24. Marine equipment distribution building (GCD)
25. B.T.E. substation area
26. B.T.E. control building
27. Cryoplant compressed building
28. Cryoplant compressed building
29. Cryoplant infrastructure
30. PFC coil fabrication building
31. Site services building
32. Hot batch cooling house
33. Cooling water pump station
34. Control building
35. Office building
36. Diagnostic building
37. ED and welding network resistor building
38. Temporary (ED/ED)
ITER Tokamak (Basic Machine) and the Surrounding Building
Cross-section of the basic machine with Vacuum Vessel
Layout of the magnet auxiliary systems
## Main Magnet Features

| Conductor | Circular Cable in Conduit, about 1000 strands, 45-70kA  
| Nb3Sn for CS, TF, NbTi for PF and CC  
| TF thin circular jacket. CS and PF thick square jacket |
| Cooling  | Supercritical Helium, inlet temperature 4.5K |
| Insulation | Glass-polyimide with epoxy/ cyanate ester resin |
| TF | D shaped, massive case surrounding winding  
| Radial plates to protect conductor insulation, double pancakes |
| CS | Stack of 6 circular coils, vertical pre-compression structure to hold coils in contact, no case, hexapancakes |
| PF | Circular coils, double pancakes, no case, supported on TF. 2 in hand windings, no inner joints |
| CC | Square coils around circumference, correction of error fields from tolerances on TF, CS, PF |
ITER Conductors-1

• ITER coils are wound from Cable-In-Conduit Conductors (CICC’s), relying on superconducting multifilament composite strands mixed with pure Cu strands/cores.
• The strands are assembled in a multistage rope-type cable around an open central cooling spiral.
• The cable and its spiral are inserted inside a stainless steel conduit which provides helium confinement.
**ITER Conductors-2**

- TF coils rely on Nb$_3$Sn strands and a modified 316LN, round-in-round jacket,
- CS coil modules rely on Nb$_3$Sn strands and a JK2LB (high Mn), round-in-square jacket.
- PF coils rely on NbTi strands and a 316L, round-in-square, jacket.

**TF Conductor**
- Bronze Nb$_3$Sn strand developed by EAS, EU
- Internal-tin Nb$_3$Sn strand developed by OST, US

**PF Conductor**
- NbTi strand developed by VNIINM, RF
TF Coils

Radial plates and conductor

Joint and manifolding region

Upper OIS

Intermediate OIS

Gravity support leg

Pre-compression Rings

Inner poloidal keys
TF Coil Winding Pack

Inner Leg Cross Section

TF Coil

TF Winding Pack

Winding Pack Assembly
CS Coils

He inlet manifolds

terminals and busbars

Single CS Module

CS stack, 6 modules, supports and precompression flanges

Upper hangers

Vertical precompression flanges

Lower centring mechanism
PF Coils

- P6 coil and supports
- 2 in hand conductor winding
- Pancake joints
- PF 6 winding
- Support clamps
- Terminals
- He inlets
Correction Coils

- 320kAT
  - opposite pairs in anti-series
  - 9 independent sets
  - correct toroidal and poloidal harmonics in poloidal field

- 200kAT
Feeder Terminations

- Main cryostat wall
- Cryostat extension
- CTB
- S bend box
- Current leads
4 large He cooling loops for the ITER magnets: TF casing, TF winding pack, PF & cc, CS.

T = 4.3K
Each TF coil experiences a bursting force (Fz) as well as a resultant centring force (Fx) towards the centre of the machine. The resultant centring forces are reacted by the cylindrical vault formed by the inboard straight legs of the TF coils.

| \( \Sigma Fx \) | -402.8.  
| -201.4/ -201.4 |
| \( \Sigma Fy \) | 0.0  
| 0.0/0.0 |
| \( \Sigma Fz \) | 0.0  
| +205.3/ -205.3 |
| \( \Sigma Mx \) | 0.0 |

Top half/bottom half
• Most ITER components are contributed *in-kind* by the seven ITER Parties through their respective Domestic Agencies (DA’s).

• The IO is responsible for overall design and integration and for defining the technical requirements.

• The DA’s are responsible for procuring the components and for delivering them to the IO.

• In-kind procurement sharing was negotiated among ITER Parties and is cast in the so-called *ITER agreement.*
• In-kind Procurement process is in two steps:
  – First step is the issuance of the so-called Procurement Arrangement packages (PA’s) between the IO and the DA’s (within framework of ITER agreement),
  – Second step is the issuance of contracts between the DA’s and their suppliers (following DA rules).
• Issuing PAs between IO and DA is proving very time-consuming
  – DAs reluctant to commit to schedule but IO cannot resolve interface issues between DAs without this
  – Procurement system does not favour competitive tenders. Das concerned about costs but locked in system that prevents effective reduction
**Total Value of Magnets**
- 48 coils / 6 major systems

**Procurement Arrangements**
- TF Conductors – 215kIUA
- PF Conductors -74kIUA
- CS Conductors – 90kIUA
- TF Winding -168kIUA
- TF Structures -99kIUA
- PFMagnets 1&6 -13kIUA
- PFMagnets 2,3,4,5 -33kIUA
- Correction Coils – 3 kIUA
- Central Solenoid – 40kIUA
- Feeders & Sensors – 44kIUA

**TOTAL ~779kIUA = 1000MEuro**
In magnets we have

TF coils EU, JA (conductor CN, EU, JA, KO, RF, US)
PF coils EU, RF (conductor CN, EU, RF)
CS coils US (conductor JA)
Correction Coils CN
Feeders CN

Procurement distribution by value
TF Coils: a Worldwide collaboration

[Map showing collaborative efforts among countries for TF coils]
Present Status of Magnet Procurement Arrangements
and industrial contracts

**TF Conductor**
Signed with CN, EU, JA, KO, RF (93% of supply). US waiting for sign from heaven.
JA in production, RF in production, KO contracts placed

**TF Coils**
Signed with EU and JA. JA contract placed

**TF Structures**
Signed with JA. JA contract placed

**PF Conductor**
Signed with CN, EU due to sign start May
CN contract placed

**PF Coils**
EU due to sign end May
RF due to sign Sept

**CS Conductor**
JA due to sign in July

**CS Coils**
US not yet ready to sign
Design Finalisation and Preparation for Manufacturing
Objective of Design Work 2007-9

Complete design and analysis....achieve an approved design....detailed at the
level of ‘build to print’
- All major features defined
- Contains sufficient detail to allow manufacturing drawings to be done
- Checked for design integration (major task due to complexity of in-
cryostat systems)
- Major structural features analysed
- Interfaces defined
- Assembly procedures reviewed
- Tolerances defined (between magnets and other systems and within the
magnets themselves, between systems and between subcomponents)
- Manufacturing concepts available and assessed as feasible

Status
TF Coils complete
PF Coils complete
CS Coils complete
CCs and supports complete Sept 2009
Feeders and CTBs complete early 2010
Example of ‘after manufacture’ outer surface tolerances for a single TF coil

ON ASSEMBLY each sector (including a TF Coil pair) will be aligned relative to its best-fit nominal position with the following total tolerances:
- radial ± 3 mm
- vertical ± 2 mm
- toroidal gap in the wedged region of the inner leg 2 ± 0.5 mm
- toroidal (outer region) ± 3 mm
Examples of Industrial Production and Design Qualification
• Nb$_3$Sn strand specifications are functional and call for
  - Diameter (un-reacted, Cr-plated)  \[0.820 \pm 0.005 \text{ mm}\]
  - Cu-to-Non-Cu volume ratio  \[1.00 \pm 0.10\]
  - $I_C$ at 4.22 K and 12 T (ITER Barrel)  \[> 190 \text{ A}\]
    (at 4.2 K and 12 T on ITER barrel)
  - Hysteresis loss per strand unit volume  \[< 500 \text{ mJ/cm}^3\]
    (± 3 T at 4.2 K cycle on a sample longer than 100 mm)
  - RRR (after Cr-plating & heat treatment)  \[> 100\]
TF Conductor cross-section (KODA)

Multistage twisted cable

Contained in a steel jacket

Jacket pre-assembled by butt welding (in a straight line ~800m long) and then pulling the cable inside. A compaction machine then pushes the jacket onto the cable.
Status of RF Jacketing Line, Jacketing & Spooling

RF Jacketing Line under construction at High Energy Physics Institute in Moscow
Status of RF Jacketing Line, Jacketing & Spooling

Workshop inside

Mar 2009
TF & PF Conductor Activities in Heifei, China

TF & PF Winding Building

Winding & Compaction Machines

Jacketing Line
JA Compaction machine

Compaction rollers (for TF conduit)
Status of building construction for JA jacketing line
(9 March 2009)
Status of JA jacketing facility preparation

- First automatic orbital TIG welding machine has been completed.
- Preliminary welding test using TF jacket with a thickness of 1.9mm was started.

Macro photos of welded joint

Inside surface of welded joint
Precompression Ring R&D
(EU and ENEA Frascati)

OBJECTIVE
- To confirm that a uniaxial glass fibre precompression ring can meet the pre-loading requirements (about 0.4% strain, 440MPa stress) at room temperature with a factor of ~4 to failure
- To confirm absence of creep
ENEA PCR test facility (1/5 full scale rings)

18x58t hydraulic cylinders

Position sensors accuracy 0.1mm
Test of second ring

R2 Ring UTS test

Failure data

- Radial load: 425 ton
- Radial stress: 77 MPa
- Hoop load: 68 ton
- Hoop stress: 1105 Pa
- Radial displ.: 9.7 mm
- Strain: 1.9%

\[ \text{Mean hoop stress [MPa]} \]

\[ \varepsilon [\%] \]
Failure mechanism

FAILURE DATA
Radial load 425 ton
Radial stress 77 MPa
Hoop load 68 ton
Hoop stress 1105 Pa (design 440MPa)
Radial displ. 9.7 mm
Strain 1.9 %

Glass fibre winding anchoring point embedded in ring was a crack initiator.
PF Insert Test
(EU, JA, RF DAs)

Single layer insert coil

Closely corresponds to PF6 conductor (NbTi)

Tested in the bore of CSMC facility in Naka July 2008
**PF Conductor Status**

- PF Insert (PFI) coil, manufactured by EU from a RF cable jacketed by EU.
- PFI performance conforms to extrapolated strand performance.
ASIPP, CN manufactured a pair of 60kA HTS trial leads, tested in December 2008.

Views of 68 kA
ITER TF Trial Lead

Views of Test CTB

See 2LPT06
Micrographic Analyses of Bent Bronze Strand (courtesy of M. Jewell)

Cable Modeling (courtesy of H. Bajas, ECP)
Finite element based model by LT Calcoli (L. Semeraro) 108 strands, each strand modeled with solid elements (and single equivalent properties), multiple contact surfaces to each other and compaction tool (jacket). Total length of 400 mm is modeled. The square shape of the conductor is achieved through a rolling process.
Radiation Resistant Insulation  
(EUDA, ATI, CEA)

Objectives

Epoxy resin is at the limits of its radiation resistance at the ITER fluence level of 10 MGy ($10^{22}$ n/m$^2$). Higher resistance is available from cyanate ester based resins

Cyanate ester resins are expensive but cost can be reduced by blending with epoxy

Incorrect curing of cyanate ester can lead to exothermic runaway reaction. Impregnation of a TF winding section under industrial conditions to demonstrate reaction can be controlled
Radiation Resistance of Epoxy and Epoxy-Cyanate Ester Blends

The epoxy – CE blends can achieve about x2 the ITER design basis (1x10^{22} n/m²)
Fabrication of a Large Test Piece to Gain Industrial scale experience

(provided by CEA)
After Impregnation with CE - Blend

(provided by CEA)
Conclusions

Blended CE offers same radiation resistance as pure CE resin. Other features
- Pot life >>24hrs
- Implied cost increase ‘a few million’ euros for ITER TF coils

Impregnation on an industrial scale can be performed successfully