Contributions

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Outlines

• ITER Tokamak Project and site
• Magnet System
• Toroidal Field coils design
• Engineering manufacture challenges
• Material development
  ▪ TF coil case cryogenic material,
  ▪ Electrical Joints material,
  ▪ Helium inlets welds,
  ▪ High Voltage feedthroughs insulation,
  ▪ Composite precompression rings material

• Summary
ITER Tokamak Project and site

• Magnet System
• Toroidal Field coils design
• Engineering manufacture challenges
• Material development
• Summary
ITER: The Way to Fusion Power

The ITER project represents the frontier in fusion energy generation, and will deliver an international scientific laboratory that demonstrates the feasibility of hydrogen fusion as a source of electricity in the 21st century.

Technical program objectives:

- Achieve extended burn of D-T plasmas, with steady state as the ultimate goal.
- Integrate and test all essential fusion power reactor technologies and components.
- Demonstrate safety and environmental acceptability of fusion.
- Integrated device answering all feasibility issues needed to define a future DEMO reactor (for instance, the 14 MeV n-resistance for in-vessel components).
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Over 60 years of research on tokamaks
D-T Fusion reaction

**Lawson criterion for ignition condition**

\[ n \cdot T \cdot \tau_E > 3 \times 10^{21} \text{ m}^3 \text{ keV s} \]

- \( nT \sim \text{Plasma Pressure} \)
- \( T \sim (\text{Cross Section})^{1/2} \)
- Confinement \( \tau_E \sim nT/P_{\text{heating}} \)

**Fusion energy gain**

\[ Q = \frac{P_{\text{fusion}}}{P_{\text{heat}}} = \frac{5 P_\alpha}{P_{\text{heat}}} \]

**\( \alpha \)-heating fraction**

\[ f_\alpha = \frac{P_\alpha}{P_\alpha + P_{\text{heat}}} = \frac{Q}{Q+5} \]

**Lithium breeding**

- Deuterium
- Tritium
- Neutron: +14.1 MeV
- Alpha: +3.5 MeV

**Plasma heating**

**Scientific Breakeven**

<table>
<thead>
<tr>
<th>Q</th>
<th>( f_\alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17%</td>
</tr>
<tr>
<td>5</td>
<td>50%</td>
</tr>
<tr>
<td>10</td>
<td>60%</td>
</tr>
<tr>
<td>20</td>
<td>80%</td>
</tr>
<tr>
<td>( \infty )</td>
<td>100%</td>
</tr>
</tbody>
</table>

Largest D-T fusion cross section (5 barns @ center of mass 120 KeV)
The Core of ITER Tokamak

Central Solenoid
Nb$_3$Sn, 6 modules

Toroidal Field Coil
Nb$_3$Sn, 18, wedged

Poloidal Field Coil
NbTi, 6

Cryostat
24 m high x 28 m dia.

Vacuum Vessel
9 sectors

Blanket
440 modules

Port Plug
heating/current drive, test blankets limiters/RH diagnostics

Torus
8 Cryopumps,

Divertor
54 cassettes

Machine mass: 23350 t (cryostat + VV + magnets)
Shielding, divertor and manifolds: 7945 t + 1060 port plugs
Magnet systems: 10150 t / Cryostat: 820 t, 28 m high, 29 m diameter
ITER key factors

- **Total fusion power**: 500 MW
- **Fusion power/absorbed heating power**: >= 10
- **Installed auxiliary heating/current drive power**: 73 MW
- **Pulse length**: 300–3000 s
- **Average (14 MeV) neutron wall loading**: 0.57 MW/m²
- **Plasma major radius R**: 6.2 m
- **Plasma minor radius a**: 2.0 m
- **Plasma volume**: 836 m³
- **Plasma current**: 15 MA
- **Toroidal field strength at 6.2 m radius**: 5.3 T

Ref [1,2]
Construction Site

Civil engineering is underway and French government has authorised the construction of Nuclear installation in November 2012

80 hectares platform
39 buildings

May 2014, ITER Organisation

Aerial view
Site construction progress

Jan 2014

PF coils construction building
(250 m long, 45 m wide, 18 m high)

Upper basemat of tokamak complex,
~ 4000 tons iron in foundation slab, now under concrete

June 2013

593 Anti seismic pads layout

Tokamak building
PF and foundation
(17 m deep, 120 x 90 m)
Global logistic on ITER Magnets

Worldwide supply of Magnets sub components from conductor to complete coils delivery to ITER site in France. Final transport from harbor over 104 kms.
• ITER Tokamak Project and site

Magnet System

• Toroidal Field coils design
• Engineering manufacture challenges
• Material development
• Summary
The ITER magnet system is made of 48 different coils:
- 18 Toroidal Field (TF) Coils,
- 6 modules Central Solenoid (CS),
- 6 Poloidal Field (PF) Coils,
- 9 pairs of Correction Coils (CCs).

Ref [3]
Why is the Magnetic system needed?

- **TF Coils** are used for charged particles confinement in plasma, operate in steady mode.
- **Central solenoid** drives the current in the plasma through transformer effect. ( transient currents)
- **PF coils** are used to control radial position equilibrium of plasma, as well as for plasma shaping and vertical stability.
- **Correction Coils** are used to correct field harmonics errors especially caused by assembly tolerances.
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Overview of Feeder system

ITER magnets are supplied with current and supercritical LHe @ 0.6MPa by 31 Feeders.

- The magnet Feeders include
  - Nb–Ti CICC busbars
  - Bi-SCCO 2223 Ag-Au(5.4%) tapes HTS current leads.

68 kA Trial Lead Developed by ASIPP

HTSC 68kA current leads

Detail of CC Feeder
• ITER Tokamak Project and site
• Magnet System

Toroidal Field coils design
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ITER TF coil design features

- 18 TF superconducting coils cooled by supercritical LHe flow (4.5 K, 0.6 MPa)
- Nominal DC transport current of 68 kA
- Peak magnetic flux density of 11.8 T
- ~ 82 kms of Nb3Sn Cable in Conduit Conductor (CICC)
- Stored magnetic energy of 41 GJ (comparison with 10.5 GJ in the 27 km tunnel of the Large Hadron Collider at CERN),
- Large 316LN stainless case structure encloses each winding pack, actively subcooled at 4.5K, and wedged to react large 410 MN centripetal e.m loads
- Overall weight ~ 5700 tons, 320 tons each
Toroidal Field Coils main components

- Fig. 1 Wound conductors before heat treatment and insertion into radial plate.

Fig. 2 Radial plate

Fig. 3 Winding pack formed of 7 radial plates containing conductors.

Fig. 4 Winding assembly shape

Fig. 5 Cable in conduit made of 900 Nb$_3$Sn strands in multistages with central channel into 316LN jacket.
Coil case operating stresses

Structural integrity of TF coils checked through extensive 3D finite element modelling at both operation and accidental conditions

Stress assessments performed per ITER Magnet Structural Design Criteria

- Nominal steady **tensile operation hoop stress** in the poloidal direction **(in plane)** up to 680 Mpa in straight leg.

- A cyclic bending component from the poloidal field **(out of plane)** up to 450 Mpa stresses in outer leg.

- A complex cyclic shear stress at the keys and pins that link the TF coils together with **stress intensity variation** of +/- 70 Mpa.

**Fig 1. Tresca Stress contour on TF structure at End of Burn plasma event.**
Operating strain of TF coils

• The irreversible strain limit of Nb3Sn strands plays a crucial role on the high field TF magnet operating design and influence on their manufacture stages.

In addition to intrinsic strain into strand, the cabling and operation conditions effects result in a differential strain of about -0.6 %, enough to cause ~25% loss of $J_c$, or 1-2 K on $T_c$ in comparison to the strand performance.

![Reduced $I_c$ versus intrinsic applied strain (credit from Twente Univ. Paper IEEE Transactions on Applied Superconductivity, 07/2009)](image)

Ref [4,5]
• ITER Tokamak Project and site
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Engineering manufacture challenges

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TF conductor manufacture process
TF CICC production process

Cable Insertion & Jacket Assembly

1. Welding
2. Cable Insertion
3. Compaction
4. Spooling

Stage 5: x6 around Central cooling spiral + stainless steel wrap

(Courtesy of H. Matsuda, NSE)

TF strand production status

463 tons (95000 kms) of Nb3Sn strands, 95% of needs

(Billet Weight Distribution By DA)

(Courtesy of G. Bevillard, IO)
# Nb$_3$Sn CICC features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{op}}$ (KA)</td>
<td>68</td>
</tr>
<tr>
<td>Type strand</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>Critical current at 12 T for Nb$_3$Sn strand @ 4.22 K</td>
<td>&gt; 190A</td>
</tr>
<tr>
<td>A non copper (mm$^2$)</td>
<td>235.33</td>
</tr>
<tr>
<td>A total (mm$^2$)</td>
<td>508.32</td>
</tr>
<tr>
<td>Strand Diameter (mm)</td>
<td>0.82</td>
</tr>
<tr>
<td>Cu:nonCu Ratio</td>
<td>1.0</td>
</tr>
<tr>
<td>Number of SC Strands</td>
<td>900</td>
</tr>
<tr>
<td>Cable Pattern Core</td>
<td>$((2 \text{sc}+1 \text{cu})\times 3 \times 5 \times 5 + \text{core}) \times 6$</td>
</tr>
<tr>
<td>Cable Pattern Core Core</td>
<td>$3 \times 4$ cu wires</td>
</tr>
<tr>
<td>Central spiral (mm)</td>
<td>9 x 7</td>
</tr>
<tr>
<td>Petal SS wrap</td>
<td>0.05 mm thick, 50% cover</td>
</tr>
<tr>
<td>Cable SS wrap</td>
<td>0.08 mm thick, 40% overlap</td>
</tr>
<tr>
<td>Void Fraction (%) in Annulus</td>
<td>33.1</td>
</tr>
<tr>
<td>Cable diameter (mm) / OD 316L jacket</td>
<td>40.5 / 43.7</td>
</tr>
</tbody>
</table>
TF coil winding manufacture key features
Winding production steps

Three TF construction sites at ASG (EU, Italy), Mitsubishi (JA) and Toshiba (JA)

Winding machine lines

Nb$_3$Sn heat treatment furnaces

Conductor transfer into the radial plates

Courtesy of F4E

Courtesy of JADA
**Challenges of winding Heat treatment**

- **Wind & React technology** of individual double pancakes (760 m) require large furnaces (fig 1, 2) for **curing of Nb\textsubscript{3}Sn @ 650+/- 5 degC for 200 hours step**

- **Tight dimensional control of windings** manufactured and heat treated to manage final shape before insertion (total length control better than 600 ppm).

![Fig 1. Heat treatment Ar gaz. furnace](courtesy of EUDA)

![Fig 2. Heat treatment vaccum. furnace](courtesy of JADA)
Turn insulation and insertion tool

- Highly engineered automated turn insulation machine using composite Polyimide / S-glass half interleaved insulation tapes (1.85 mm thick, 2.2 KVDC rated insulation design)
- Additional Stainless steel co-wound tapes for sensitive quench detection

Sample of short beam impregnation trials

Fully automated insulation machine with insertion

Courtesy of F4E
Accurate Radial plates sectors assembly

- Development of state of art welding technologies to join the radial plate forgings sub-sections (narrow gap TIG welding, electron beam welding or laser welding) over 120 mm thickness per ISO5817 quality lev B.
- After winding heat treatment, double pancake geometry is measured by laser scan (10 micrometers/m) then RP final machined over 14 m with portal machine (0.1 mm accuracy).

Fig 1. a) Laser scanning of double pancake, b) Resultant winding survey geometry

Fig 2. Radial plate segments

Fig 3. Portal machine on RP production courtesy of CNIM

Fig 4. n-GTAW + Laser joint (24kW) weldment
High technology Laser closure welding

- More than 1.5 kms of 2 mm deep weld lines to enclose CIC conductor into radial plates by 2 kW fiber Laser welding with optical guidance along 0.2 mm gap

Fig. 1  Laser welding of the cover plates with 3 welding robots

a) Cross section of covers fitted on grooves

b) Typical closure cover laser welding bead

Courtesy of F4E
Large Coils cases manufacture challenge

- Mass production of 4500 tons of large high strength 316LN steel structure
- NG-TIG welded assembly of forged plates up to 200 mm thick and tight deformation control of ~3 mm to satisfy final shape.

Fig. 1 Cut view of final encased winding

Fig. 2 TFC sub assemblies parts

Fig. 3. Top inboard assembled segment

15m, 210 tons
Wide range challenges on coil integration

- From 2017 onwards, assembly of 9 TF coils pairs equipped with vacuum vessel using dedicated jigs, each of 980 tons with tight assembly tolerances requirements (< 2 mm) and use of customized shimming capability within $1/10^{th}$ mil accuracy.

Fig 1- TF sector in-pit Assembly tool

Fig 2- View of TF assembly
• ITER Tokamak Project and site
• Magnet System
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Material development

• Summary
TF case high strength material features
Structural cryogenic material

The SS316LN structural materials withstand large magnetic forces at 4K requiring both high strength (from 900 MPa YS) and good fracture toughness (>180 Mpa.m\(^{0.5}\)), consolidated by extensive QC mechanical tests campaign at 4K (tensile, FCGR, S-N curves (see back up slide).

Fig 1. Relationship between strength at 4K and C+N content – JSME construction code (JADA)

Fig 2. properties class of TFC structure material

Fig 3. Multi axis forging on ingots after melted electric arc furnace refinement process.

<table>
<thead>
<tr>
<th>Class</th>
<th>Yield Strength at 4K</th>
<th>Color</th>
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</thead>
<tbody>
<tr>
<td>C1</td>
<td>&gt; 1000 MPa</td>
<td>Red</td>
</tr>
<tr>
<td>C2</td>
<td>&gt; 900 MPa</td>
<td>Blue</td>
</tr>
<tr>
<td>C3</td>
<td>&gt; 700 MPa</td>
<td>Grey</td>
</tr>
<tr>
<td>C3A</td>
<td>And @ RT &gt; 260 MPa</td>
<td>Yellow</td>
</tr>
<tr>
<td>C4</td>
<td>&gt; 500 MPa</td>
<td>Green</td>
</tr>
</tbody>
</table>
TF coil electrical joint manufacture challenges
Electrical joints design

- Twin box electrical joints based on bimetallic Oxygen Free High Conductivity Copper C10100 series sole (RRR: 200-300) explosion bonded to Stainless steel 316L(N).
- Specified joint resistance $R_j < 2 \text{ nOhms}$
- Joints operate at DC with low losses ($< 10 \text{ W peak}$) and are cooled in series with the winding exits conductors.
TF Joint manufacture steps

1- Cable inserted into twin box after Cr outer strand surface removal before closure welding of cover and connection to TF coil jacket.

2- Clamped cover assembly under press (200 tons).

3- Cross section view of assembled twin box.

4- First of series joints on TF coil pancakes, (Courtesy of F4E).
Bi-metallic joints material benchmarking

- Extensive quality check on bi-metallic material in collaboration with CERN on various supply lines to constitute a database, especially on RRR values increase after heat treatment.

Fig 1. Micrograph of explosion welding interface with shear wave effect.

Fig 2. RRR values vs. Hardness HRF measurement on OHFC coppers used from joints bi-metallic suppliers.

Presented at ICMC Oral ID 404-6 by S. Langeslag 'Extensive characterisation of Copper-clad plates, Bonded by the Explosive Technique, for ITER Electrical Joints'
TF coil helium inlet manufacture challenges
Helium Inlets manufacture challenges

- One helium inlet supply (16 g/s, 4.5 K @ 0.55 Mpa) per double pancake length of 720 m (see Fig. 1).
- Limited pressure drop required (measured 660 Pa vs 160 Pa/m of CICC)
- Fatigue strength requirement of heat treated penetrating fillet weld under 30000 lifetime cycles.
Crucial selection of inlet weld material

- ER317LN (DIN 1.4453) austenitic filler metal with low C (0.021 %Wt) chosen to limit grain boundary sensitization forming chromium-rich intermetallic precipitates ($M_{23}C_6$) (fig. 1)

- Intergranular corrosion also prevented after a heat treatment of 1000 hours at 700 °C

- No $\delta$-ferrite allowed as it changes to a brittle phase at 4 K during reaction heat treatment

Ref [9]
Cyclic fatigue test of inlet prototypes

- Design by experiment through Statistical fatigue mechanical tests [see reference book on Fatigue Strength of Welded Structure by Maddox, 1991]

- Fatigue test at 4K of 6 prototypes at nominal strain $(10.2+/−2.3) \times 10^{-4} \varepsilon$ over 261,000 cycles representative of a population of 126 inlets. (design lifetime of 30,000 cycles)

- All 6 samples successfully tested at KIT institute (D), two of them with 15% extra strain margin up to 600,000 cycles.

Fig 1. TF inlets fatigue test samples

Fig 2. Fatigue tensile test machine layout (courtesy of KIT)

Ref [10,11]
High Voltage design challenges
High Voltages features in TF coils

- Operating transient voltage up to 18kV to ground in accidental short condition.
- Multiple high voltage wires feedthroughs (see fig.1) through 6 mm thick ground insulation is a potential risk at manufacture;
- Hence 2 stages high quality Vacuum Pressure impregnation of feedthroughs insulations (DP and Winding pack), then final wire connection wet insulation (see next slide)
- Extra electrical tracking length criteria as a mitigation against de-bonding / cracking of insulation system during a He leak under atmosphere. (154 mm @ 19kV, SF = 4)
TF terminal region, feedthroughs

Fig.1 Terminal coil joint region layout

Fig.2 cut view of feedthroughs with solid barrier insulation

Fig.3 First stage of HV wire feedthroughs manufacture

TF terminal region, feedthroughs

Termination busbars joint
Interpancakes joints

HV wire feedthroughs
Stringent acceptance high voltages testing

- In addition to DC and AC repeated manufacture coils tests (see Tab. 1), each winding will be Paschen proof tested up to 8KV to ground as a worst case electrical failure combined with loss of vacuum insulation.

- Importance reference of HV Paschen tests performed onto W7-X coils project revealing insulation weaknesses at exits conductors.

Tab 1. Acceptance and Manufacturing Test Voltage Levels

<table>
<thead>
<tr>
<th></th>
<th>DC Acceptance Test kV</th>
<th>AC Acceptance Test kV</th>
<th>DC Manufacturing Test kV</th>
<th>AC Manufacturing Test kV</th>
<th>Paschen Manufacturing Test kV</th>
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</thead>
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<tr>
<td>Turn to RP</td>
<td>&gt;2.2</td>
<td>0.4</td>
<td>&gt;2.2</td>
<td>&gt;0.4</td>
<td>2.2</td>
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<tr>
<td>DP to DP</td>
<td>&gt;3.4</td>
<td>0.8</td>
<td>&gt;3.4</td>
<td>&gt;0.8</td>
<td>3.4</td>
</tr>
<tr>
<td>WP to ground</td>
<td>&gt;19.0</td>
<td>2.5</td>
<td>&gt;19.0</td>
<td>&gt;2.5</td>
<td>8.0</td>
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Precompression composite rings
Precompression rings composite material

- Innovative composite material versus traditional aerospace manufacture sizes
- Purpose to preload each TF flange up to 37 MN radial load and to prevent separation gaps of the poloidal keys between coils.
- Benefit is hampered eddy currents and reduction of local fatigue

Fig. 2. Manufacture from S2 fibre-Glass unidirectional preimpregnated composite tows steering by Advanced Fiber Placement (AFP)

Ref [16, 17, 18]
Advanced design assessment method

- Operating **430 Mpa hoop stress** with safety factor of 3-4 to rupture
- Use of Tsai-Hill interactive phenomenological structural failure strength criteria to match anisotropic composite material properties at RT & 4K.

\[
\left(\frac{\sigma_x}{S_1}\right)^2 + \left(\frac{\sigma_y}{S_2}\right)^2 + \left(\frac{\tau_{xy}}{S_{12}}\right)^2 + \left(\frac{\tau_{xz}}{S_{13}}\right)^2 + \left(\frac{\tau_{yz}}{S_{23}}\right)^2 - \frac{\sigma_x \sigma_y}{S_1 S_2} \leq 1
\]

Fig.1 Multi scale models analysis from Micro, Meso to Macroscale properties
From test campaign to fabrication

a) 1/5th composite sub scale prototype ring - b) Picture of failed 1/5th ring

c) Advanced Fiber Placement Technology (AFP) on a flat annular tool (EADS Airbus)

b) Testing jig installed at ENEA (It, Frascati) for mock-up rupture test
Summary

- ITER TF coils system procurements packages under way since 2008 rely on worldwide collaboration (JA, EU, KO, CN, RF, US)
- Most challenging and innovative superconducting projects in the world today within magnetic confinement fusion power production.
- The qualification of last manufacture steps is on going and the construction phase of first series winding components has started at main workshop facilities in Europe and Japan.
- Coil design success relies on large forefront material developments at cryogenics temperature and challenges on engineering fabrication processes under current coils qualification phase.
- Technical challenges are being overcome but many others are ahead of the coming first of series coils by beg. 2016, from their integration from 2018, till the first plasma commissioning from 2021.
- > €1B equivalent total industrial TF contracts is anticipated amongst all contributors.
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Precompression rings
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Superconducting Magnets: Demonstrating hydrogen fusion will bring a star to Earth . . .

Thank you . . . and a path to clean, safe, abundant energy.

Email contact: Arnaud.Foussat@iter.org
BACK UP SLIDES
Fatigue experimental design data

Large amount of experimental fatigue data on 316LN series at 4K to benchmark especially for the fatigue and LEFM models benchmarking.

**Fig. 1** S-N design fatigue curve at 4K of 316LN forged material

**Fig. 2** Crack growth rate measurement vs cycle number at 4K of 31LN

Crack propagation rate of transition $i$:

$$
\left( \frac{da}{dN} \right)_i = \begin{cases} 
0 & \text{for } \Delta K_i \leq \Delta K_{th}(R_i) \\
C(\Delta K_i)^m & \text{for } \Delta K_{th}(R_i) < \Delta K_i
\end{cases}
$$

depending on stress ratio $R_i$