The ITER Project:
moving forward at full speed

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Presentation outline

1. ITER Project overview
2. ITER’s Magnets: specifications, challenges, and breakthroughs
3. Status of construction and manufacturing
ITER Project- overview
One of the greatest challenges of our civilization
Fusion in the Universe

- Fusion powers the Sun and stars from billions of years.
- In a fusion reaction, two light atomic nuclei combine, form a heavier nucleus and release energy.
- The Big Challenge: to reproduce in a fusion machine (Tokamak*) a similar reaction on Earth.

*Tokamak: a Russian acronym for «Toroidal Chamber, Magnetic Coils».

$\Delta E = \Delta mc^2$

A tiny loss of mass  
A huge liberation of energy
Fusion on Earth

1 gram of fusion fuels = 8 tons of oil

- A plasma of Deuterium + Tritium (hydrogen isotopes) is heated to more than 150 million °C.
- The hot plasma is shaped and confined by strong magnetic fields.
- Helium nuclei sustain burning plasma.
- Neutrons transfer their energy to the Blanket.
- In a fusion power plant, conventional steam generator, turbine and alternator will transform the heat into electricity.

\[
\begin{align*}
\text{Deuterium} & \rightarrow \text{Tritium} + \text{Helium nuclei} + n \\
^{2}\text{H} & \rightarrow ^{3}\text{H} + {^4}\text{He} + 3.5 \text{ MeV} \\
& \quad + n + 14.1 \text{ MeV}
\end{align*}
\]
Fusion’s advantages

- A new energy source of massive, predictable and potentially continuous power
- Intrinsically safe, environmentally responsible
- Almost limitless supply of fuel, widely distributed around the globe
- No CO₂ or other greenhouse gases emission
- No long-lasting high-activity radioactive waste

A plasma in the European tokamak JET
ITER
A multinational scientific collaboration without equivalent in history
A large-scale experiment to demonstrate the feasibility of fusion energy

Geneva, November 1985...
ITER
Global challenge, global response

- 28 June 2005: The ITER Members unanimously agreed to build ITER on the site proposed by Europe
- 21 November 2006: The ITER Agreement was signed at the Élysée Palace, in Paris.

The seven ITER Members represent more than 50% of the world’s population and about 85% of the global GDP

China EU India Japan Korea Russia USA
To demonstrate the scientific and technological feasibility of fusion power for peaceful purposes

ITER is the only magnetic fusion device under construction aimed to produce a burning plasma.

Input (heating power): 50 MW
Output (fusion power): 500 MW
The ITER Tokamak

Vacuum Vessel: ~ 8 000 t.
TF Coils: ~ 18 x 360 t.
Central solenoid: ~ 1 000 t.
Etc.
Total ~ 23 000 t.

R=6.2 m, a=2.0 m,
I_p=15 MA, B_T=5.3 T,
23,000 tonnes

3,5 times the weight of the Eiffel Tower!
An intense magnetic field, generated by powerful superconducting magnets shape and confine the hot plasma, and keep it away from the vacuum vessel wall.

- 1 central solenoid, 13 m high, 1,000 tons, powerful enough to lift an aircraft-carrier out of the water
- 18 Toroidal Field Coils, 17-metre high, 360 tons each.
- 6 Poloidal Field Coils, 8 to 24 m in diametre, 200 to 400 tons.
• The 7 ITER Members make cash and in-kind contributions (90%) to the ITER Project. They have established Domestic Agencies to handle the contracts to industry.

• The ITER Organization Central Team manages the ITER Project in close collaboration with the 7 Domestic Agencies.

• The ITER Members share all intellectual Property generated by the Project.
A unique formula

ITER is being built through the in-kind contributions of the seven Members of the ITER Organization.

China, India, Japan, Korea, Russia and the United States each have responsibility for ~ 9% of procurement packages.

Europe’s share, as Host Member, is ~ 45% (construction and manufacturing).
Naval construction-size components...

Inside the Assembly Hall, giant tools will handle loads up to 1,500 tons
...watch-like precision

Laser measurements of grooves in TF Coil radial plates. Tolerances are in the 1/10th millimetre range.
The integration challenge

BLANKET MODULES
MANIFOLD
DIVERTOR
INTERNAL COILS
INTERFACES
Managing collaboration
(The TF Coils example)
Managing the need for change

Action Plan 2015

Set clear priorities and timeline for reform

✓ Reorganized and integrated the ITER Central Team with Domestic Agencies:
  ✓ Clear decision processes and accountability
  ✓ DG/DDG, Executive Project Board, Reserve Fund, Project Teams
✓ Finalized and stabilized ITER critical component design
✓ Conducted comprehensive integrated bottom-up review of all activities, systems, structures, and components to build the ITER machine
  ✓ Developed an optimized resource-loaded schedule for timely, cost-effective construction and operation through start of D-T plasma.
✓ Developed and promoted a strong, organization-wide nuclear project culture
A staged approach to DT plasma

Extensive interactions among IO and DAs to finalize revised baseline schedule proposal

✓ Schedule and resource estimates through First Plasma (2025) consistent with Members’ budget constraints

✓ Proposed use of 4-stage approach through Deuterium-Tritium (2035) consistent with Members’ financial and technical constraints
In 2016, 18th & 19th ITER Council endorse updated Schedule

Best technically achievable path forward to First Plasma (FP) in December 2025

Staged approach from FP to D-T commissioning December 2035

The updated Schedule is challenging but technically achievable.

Members now have all the elements needed to go through their domestic processes of obtaining approval for the selected Resource-Loaded Integrated Schedule

ITER Council convenes twice a year in June and November at ITER Headquarters
ITER’s Magnets: specifications, challenges, and breakthroughs
• The ITER magnet system is made up of
  – 18 $\text{Nb}_3\text{Sn}$ Toroidal Field (TF) Coils,
  – a 6-module $\text{Nb}_3\text{Sn}$ Central Solenoid (CS),
  – 6 $\text{Nb–Ti}$ Poloidal Field (PF) Coils,
  – 9 $\text{Nb–Ti}$ pairs of Correction Coils (CCs).
ITER Magnet System – 2

• ITER magnets are supplied with current/cryogenic fluids by **31 Feeders**.

  • The magnet Feeders include
    
    – Nb–Ti CICC busbars (MB & CB),
    
    – Ag-Au(5.4%) BiSCCO 2223 HTS current leads.

ITER Feeder System

68 kA Trial Lead Developed by ASIPP
ITER Conductor Supply

**Nb$_3$Sn**
- 88 km, 825 t
- 215 kIUA (334 M€)

**PF Conductor**
- 65 km, 1224 t
- 81 kIUA (126 M€)
  - 10.7 km (CC)
  - 3.7 km (MB+CB)
  - 2.13 kIUA (3.3 M€)

**TF Conductors**
- 43 km, 745 t
- 90 kIUA (140 M€)

**CS Conductor**

**MB Conductor**

**CC Conductor**

**Nb–Ti**
- 43 km, 745 t
- 90 kIUA (140 M€)

**CB Conductor**
ITER Conductor Manufacture

Strand Production

Cabling

Jacket Production

Jacket Assembly

Cable Insertion

Compaction Spooling

Final Tests

MT25 Conference on Magnet Technology, August 2017
Main Features of ITER TF Coils

- The TF coil is made up of a winding pack (WP) inserted inside a thick coil case made of welded, stainless steel segments.

- Each winding pack (WP) comprises 7 double pancakes (DPs), made up of a radial plate with precisely machined grooves into which the CICC is transferred upon heat treatment completion.
ITER TF DP Manufacture – 1

Conductor Spool

DP Winding (12 m x 9 m)

Elec. Terminal

He Inlet

DP Heat Treatment

Radial Plate Section Welding

Courtesy of A. Bonito-Oliva (F4E)

Radial Plate Assembly

Transfer of HTd DP into Radial Plate
DP Turn Insulation inside Radial Plate

Cover Plate Welding

DP Ground Insulation

Hi-Post Test on Impregnated DP

Impregnated DP

DP Loading into Vacuum Impregnation Mold (radiation-hard cyanate ester resin)

Courtesy of A. Bonito-Oliva (F4E) and N. Koizumi (QST)
### TF Coil Production Status (August 2017)

<table>
<thead>
<tr>
<th>Process</th>
<th>EU</th>
<th>JA</th>
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<td>31</td>
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<td>DP Heat Treatment</td>
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<tr>
<td>WP Terminal Region Assembled</td>
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</tr>
</tbody>
</table>

**Notes:**
- 18 +1 WPs
- 1 WP = 7 DPs
- 133 DPs
- (70 EU, 63 JA)

1<sup>st</sup> and 2<sup>nd</sup> complete WPs

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**Assembly Line at ASG**

![Assembly Line at ASG](image-url)
Magnet Supports

1st TF Gravity Support

PF3, 4, 5 U shaped clamps

PF 3- PF 4 strut under welding

(below) thermal cycle and pressure test

Courtesy Zhang Bo and HTXL
PF1 Coil Status

- RFDA has completed winding of two (out of 8) PF1 Double Pancake.

1st PF1 DP Winding (September 2016)

1st PF1 DP VPI (April 2017)

2nd PF1 DP Winding (April 2017)

Courtesy RFDA & Efremov Institute
EU suppliers have completed winding of dummy double pancakes for PF5 & PF6 and have started winding of first production Double Pancakes.

PF5 Dummy DP Winding (February 2017)

1st PF6 DP Winding (April 2017)

2nd PF6 DP Winding (underway)
8th DP now complete

Courtesy F4E & B.-S. Lim (ITER-CT)
CS Coil Status

- **USIPO supplier** has completed stacking and heat treatment of **first** (out of 7) **CS Coil Module** and is proceeding with turn insulation (each module is made up of 6 hexa-pancakes and 1 quadra-pancake).

- Winding of **2nd module** is completed; winding of **3rd module** has started.

1st CS Module

Assembly platform during final inspection at Robatel Technologies

Commissioning turn over station with dummy module

Courtesy USIPO & GA
The magnet feeders are deeply integrated into the tokamak.

Courtesy of C.-Y. Gung (ITER-CT), E. Niu (CN-DA) & K. Lu (ASIPP)
First magnet component to be installed in tokamak pit will be **PF4 Cryostat Feed Through (CFT)**, which is a captive component.
PF4 Cryostat Feed-Through (Aug 2017)

- Manufacture is completed at ASIPP and shipping to IO is being prepared.

PF4 CFT

- Thermal Shields ready for Assembly

Complete

- Internal Pipes

Containment Duct Assembly

Horizontal Vacuum Duct Machining

Courtesy of C. Liu (ASIPP)
10,000 tons of superconducting magnets

10,000 tons of magnets, with a combined stored magnetic energy of 51 Gigajoules (GJ), produce the magnetic fields that initiates, confines, shapes and controls the ITER plasma.

Manufactured from niobium-tin (Nb3Sn) or niobium-titanium (Nb-Ti), the magnets become superconducting when cooled with supercritical helium in the range of 4 K (−269 °C).
Conductor Issue: degradation of large Nb3Sn CICC

The Design Challenge

- Nb₃Sn is a brittle compound that easily fractures under tension
- Form cable from wires then heat treat to make Nb₃Sn.
- Wires separated to allow Helium at 5K to flow and block AC losses
- Wires must be strongly supported mechanically

=> Challenge is to avoid filament cracks
Demonstrating the challenge is overcome

- Short (~3m) conductor lengths tested for all 8 strand types
- Tests of “insert coils” with a conductor length of ~50m, a diameter of about 1.5m and a height of about 2m.
- ‘inserted’ into the bore of a very large superconducting coil

- Close synchronisation with the industrial development of Nb$_3$Sn wire and cable
- Coil tests, in 2000-2002, led to adjustments in the wire and conductor design.
- Coil tests in 2014-2017 have confirmed the performance of the Central Solenoid conductor but leave open some issues on the Toroidal Field (TF) conductor.

CS Insert test results confirm stable behavior as a function of EM and thermal cycling

SULTAN facility with open end cap showing conductor sample hanging vertically in front
Latest TF Insert Results

- TF conductor successfully resists the magnetic forces, with an acceptable level of performance loss
- Triggering of repeated WUCD degradation by EM cycles in the TFI is more persistent than expected
- Anticipated fracture of Nb$_3$Sn material, conductors were designed with margin.
- TFI tested under much more severe set of conditions than in ITER

- Conservative extrapolation of results to ITER itself shows sufficient margin
- Higher level of degradation than foreseen, EM triggers extra WUCD degradation.

**Steps to manage degradation through better understanding**

- Extension of the present TF insert test
- Extra programme of conductor testing
- Thresholds exist for EM-WUCD interaction: use tests to establish them, adjust operation to reduce number of ‘triggers’
- If needed, new insert coil to exactly replicate the TF conductor operating life.
Structural Issue. Tolerances on structures

Where dimensional errors have an impact
- Fitting of components during assembly so that load paths still match design intention
- Inability to place component in available space
- Field errors

What drives tolerances
- Manufacturing requirements/capability
- Installation requirements/capability
- Measurement errors and component deformations under gravity
- Cumulative build up during manufacturing & assembly.... tolerances depend on other components

*TF coils & structures are the core which drive the rest*
Structural Build-up of TF Coils

Key is manufacturing of accurate radial plates to hold the conductor
- Decouple geometric uncertainties of conventional bonded WP due to insulation from WP final geometric
- Eventual solution (after many trials) is to assemble plates from sections, with squared ends, and then local machine groove continuation

Below: radial plate section

Right: assembly of sections

Completed radial plate

Accuracy <1mm in flatness and inner/outer profiles

Courtesy of F4E
• TF structure calls for mass production of ~4500 tons of large, high-strength, 316LN steel components.

• Components are made of TIG welded assemblies of forged plates up to 200 mm and require tight deformation control to achieve final shape.

• Three suppliers have been selected: MHI and Toshiba (Japan) and HHI (Korea).

• Series production of AU, AP, BU and BP sub-assemblies are underway at all 3 suppliers.
Large Structure Manufacturing

Completed BU and BP sections

Fitting test of AP on AU

Typical machining accuracy 0.5-1mm

Courtesy QST, MHI and HHI
Large Structure Manufacturing

Very accurate recent 3-D measurements
Show compliance with specifications

Courtesy QST, MHI and HHI

MT25 Conference on Magnet Technology, August 2017
Last Step: Fitting the TF Winding Pack into the Case

Vertical insertion route
- Lower WP into nose section
- Lower BU outer section onto WP
- Weld AU to BU: control distortion
- Insert AP and BP (spring into place)
- Weld AP to AU and BP to BU: control distortion
- Fill gap between winding pack and case
- Machine case

Target tolerance on interface surfaces <2mm
Status of construction and manufacturing
Tokamak Complex

Resting on 493 seismic pads, the 440 000-ton Tokamak Complex comprises 7 levels (2 underground).
Tokamak Complex
Assembly Hall

43 metres above the building’s basemat the double overhead crane is now installed
Adjacent to the Assembly Hall, the building that will house the plasma heating systems (microwave and radio frequency) is in the last stages of construction.
Steel structure installation is ongoing on what will be the largest single platform cryoplant in the world. The ITER Cryoplant will distribute liquid helium to various machine components (supraconducting magnets, thermal shield, cryopumps, etc.).
Foundation works and column construction are ongoing in the two large Magnet Power Conversion buildings that will host the AC/DC converters feeding power to the ITER magnets.
Too large to be transported by road, four of ITER’s six ring-shaped magnets (the poloidal field coils, 8 to 24 m in diameter) will be assembled by Europe in this 12,000 m² facility. Fabrication of PF Coil #5 (17 m. in diameter) has begun.
The cryostat lower cylinder (tier 1) is being welded together in the on-site Cryostat Workshop.
Who manufactures what?
The ITER Members share all intellectual property

- Toroidal Field coils (18)
- Poloidal field coils (6)
- Correction coils (18)
- Central solenoid (6)
- Divertor
- Blanket modules
- Cryostat
- Thermal shield
- Vacuum vessel
- Feeders (31)
Tooling for Poloidal Field coil #6 (350 tons, 10 meters in diameter), is now complete and being commissioned.

The first of three power transformers for the pulsed electrical network is being equipped on site.
Manufacturing progress

Poloidal Field Coil #5 getting ready for vacuum pressure impregnation

A poloidal segment of one vacuum vessel sector is fitted. Four segments, each weighing over 6 tonnes, form the full sector.

Manufacturing progress

Thousands of in-wall shielding pieces have been manufactured, passed factory acceptance, and are being prepared for shipment.

Preparing to pump: One of two full-size prototypes of the cryoline sections that will feed the torus cryopumps.

Cryostat, Cryogenic Systems, Heating and Current Drive Systems, Cooling Water System, Vacuum Vessel, Diagnostics
Manufacturing progress

Toroidal field coil high-temperature treatment to form niobium-tin supraconductor compound.

At MHI' Kobe plant one of the world's largest milling machines is turning out the main structural element of the TF magnet system.

Magnet Systems, Heating & Current Drive Systems, Remote Handling, Divertor, Tritium Plant, Diagnostics
Manufacturing progress

At Hyundai Heavy Industries, welding on the upper section of the inner shell for Sector #6.

Final testing of the first 800-ton Sector Sub-Assembly Tool, one of 128 purpose-built tools for assembly.

Vacuum Vessel, Blanket, Power Systems, Magnet Systems, Thermal Shield, Assembly Tooling, Tritium Plant, Diagnostics
Fabrication and qualification tests of PF1 winding pack stack sample were successfully completed.

Prototypes of important electrical equipment (fast discharge) have been tested and qualified at Efremov Institute – Saint Petersburg.

Power Systems, Magnet Systems, Blanket, Divertor, Vacuum Vessel, Diagnostics, Heating & Current Drive Systems
General Atomics is fabricating the 1000-ton Central Solenoid (CS). In April 2016, winding of the first CS module was completed.

The manufacturing of the piping of the cooling water circuit (36 km) are under progress in Mississippi after ASN inspection.

ITER is moving forward!
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ITER is moving forward!

Thank you for your attention

http://www.iter.org