ITER Engineering Science and Breakthroughs

Gyung-Su Lee
Chief Operating Officer / DDG
Outline

- Background: Change and Reform
- Staged Approach: First Plasma to DT Operation
- Building and Plant Construction
- Critical Components and Systems Manufacturing
- Advancement of Technology R&D Area
- Technology & Engineering Breakthroughs and Spinoffs
- Summary
Background: Change and Reform

Action Plan 2015: Set clear priorities & timeline for reform

- Reorganized and Integrated ITER Central Team (IO-CT) with Domestic Agencies
  - Clear decision processes and accountability
  - Executive Project Board, Reserve Fund, Project Teams
- Finalized and stabilized ITER critical component design
- Comprehensive integrated bottom-up review of all activities, processes and systems
  - Developed an optimized resource-loaded schedule for timely, cost-effective construction and operation through D-T plasma. Updated the 2010 Baseline (Baseline2016).
- Developed and promoted a strong, organization-wide nuclear project culture
Staged Approach: FP to DT Operation

Extensive works among IO and DAs to finalize revised baseline: Baseline2016 Schedule and Cost (OPS & OPC)

- Schedule and resource estimates through First Plasma (2025) consistent with Members’ budget constraints
- Adopted **4-stage approach** through Deuterium-Tritium Operation (2035) consistent with Members’ financial and technical constraints

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<th>Construction Phase</th>
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<td>First Plasma (FP)</td>
<td>End of Pre-Fusion Power Operation-II (FP)</td>
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<td>EO Finished and Start of Assembly II</td>
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<td>Staged Approach: FP to DT Operation</td>
<td>DT Operation</td>
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Stage I  →  Stage II  →  Stage III  →  Stage IV
# Assembly Milestone Schedule to First Plasma

## Level 0 Construction Schedule to First Plasma in 2025

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Building & Plant Construction

11 TOKAMAK BUILDING
13 ASSEMBLY BUILDING
14 TRITIUM BUILDING
15 RF HEATING BUILDING
17 CLEANING FACILITY BUILDING
19 SEISMIC ISOLATION BASEMAT
21 HOT CELL BUILDING
23 RAD WASTE BUILDING
24 PERSONNEL ACCESS CONTROL BUILDING
32 MAGNET POWER CONVERSION BUILDING 1
33 MAGNET POWER CONVERSION BUILDING 2
34 NB POWER SUPPLY BUILDING
36 MAIN ALTERNATING CURRENT DISTRIBUTION BLDG
37 NB HIGH VOLTAGE POWER SUPPLY BUILDING
38 REACTIVE POWER CONTROL BUILDING
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46 47 MEDIUM VOLTAGE DISTRIBUTION BUILDING
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52 CRYOPLANT COLDBOX BUILDING
55 PF COIL FABRICATION BUILDING
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59 60 IP GENERATOR BUILDING
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67 COLD BASIN & COOLING TOWERS
68 COOLING WATER PUMP STATION
71 CONTROL BUILDING
74 DIAGNOSTICS BUILDING
75 FD & SWITCHING NETWORK RESISTOR BLDG
Tokamak Complex Design & Construction

1. Integrated Building Design
2. Construction Design
3. Execution Design & Construction
4. As-Built Design

* Design Interface fully *FROZEN* and no more PCRs affecting Tokamak Building.
## Status of Tokamak Complex Design & Construction

<table>
<thead>
<tr>
<th>Categorization</th>
<th>Level</th>
<th>Building / MRR Acceptance Reports approval dates</th>
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<tbody>
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<td>2 Construction Design</td>
<td>• Level L3</td>
<td>• Bldg. 11, 14, 74: August 2017 (last version)</td>
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<td>• Roof</td>
<td>• Bldg. 11, 14: October 2017 (1st issue) • Bldg. 74: August 2016 (1st issue)</td>
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Tokamak Complex
Bioshield Concrete Works Completed
Construction-by-Area Approach (Worksites)

**Worksite 1**: Tokamak Main Machine,
**Worksite 3**: Hot Cell + Rad Waste + Control Buildings,
**Worksite 5**: Electrical & Power Supply Buildings,

**Worksite 2**: Tokamak Complex Plant + RF Bldg. (B15)
**Worksite 4**: Cryogenic Plant + Cooling Station
CTTA (Worksite 1) & CTTC (Worksite 2)

IO CTTC Contracts and EU-DA Building Services (TB04) Contract Co-activity Area
Tokamak Assembly Flow (B17 - B13 - B11)

- Introduction of the Tokamak components in Building 17;
- Preparation and sub-assembly of the sectors in Building 13;
- Transport of the sector sub-assemblies via 2x750t crane to the Tokamak Pit;
- Final assembly of the components/sub-assemblies in the Tokamak Pit.
Learning Curve with Sectors 6 & 7
Sub-assembly

Sector-by-Sector Assembly (KSTAR, EAST, JT-60SA) with Learning Curve by Sectors 6 & 7

Tokamak Lower In-pit Installation Activities

Tokamak Assembly Hall Activities

Tokamak In-Pit Installation Activities
Tokamak Assembly Tools Design

Sector Sub-Assembly Tool (SSAT)

Sector Lifting Tool
Sector Sub-Assembly Tool (SSAT #1)
Sector Sub-Assembly Tool (SSAT #2)
One-of-Kind Plant: Cryogenic System

ITER variable heat loads (overall heat loads)
In-kind Procurement Manufacturing

Feeders (31)
Toroidal Field coils (18)
Poloidal field coils (6)
Correction coils (18)
Central solenoid (6)
Divertor
Vacuum vessel
Blanket modules
Cryostat
Thermal shield

NAS Committee on Strategic Plan for US Burning Plasma Research, 1~2 Feb. 2018
Vessel Systems in Mass Production

Cryostat, Thermal Shields, and Vacuum Vessel Sectors & Ports
Cryostat in Mass Production

[Images of the upper cylinder, lower cylinder, lid, and base section of the cryostat, with labeled parts such as bearings, crown, bioshield, and radial walls.]
Thermal Shield in Mass Production
Vacuum Vessel in Full Production

- **Nuclear licensing as an ESPN (First In-Kind of Fusion Nuclear Pressure Vessel)**
  - The ITER VV is defined as an ESPN (Equipement Sous Pression Nucléaire) component that requires that all documents related to design, manufacturing, installation, and operation shall be reviewed and approved by an Agreed Notified Body (ANB) on behalf of the French Nuclear Authority (Autorité de Sûreté Nucléaire : ASN). → (Originally designed as a non-nuclear engineering *(French nuclear regulation applied after site selection)*)

  - As main C&S, we are applying the RCC-MR 2007 Edition that is the first application on the ITER VV construction that cause a few of major updating of C&S itself during design and manufacturing.

- **Many clients (Complex interfaces)**
  - The VV supports many in vessel systems such as Blankets, Diverters, Diagnostics, In-vessel Coils, Port Plugs, Components of Heating and Current Drivers, Fuelling, Cooling Pipes, and Assembly, etc. Many of functional and physical interfaces cause long discussion because of mainly different design maturity of each system.
    → Main technical challenges have been resolved during manufacturing process
    → All 9 VV sectors are under manufacturing and the first sector (S#6) has been achieved ~77 % of progress
Status of VV Production in KO

PS1

VV#6-PS1: Completion of manufacturing (IC-23) with meeting all required tolerance

PS2

PS3

Upper Port
Delivered from MDT (RF) to HHI (KO)

PS4

PS : Poloidal Segment

Lower Port
Manufactured by HHI (KO)
Status of VV Production in EU

PS2

PS3

PS4

Upper Port

Lower Port

NAS Committee on Strategic Plan for US Burning Plasma Research, 1~2 Feb. 2018
Superconducting Magnets in Full Production

TF Winding Pack, TF Structure, PF Coils, CS Coils, and CC-Coils
Status of TF WP Production in JA
Status of TF WP Production in EU

TF06

TF09

TF WP Instrumentation Test

TF11 (arrived for insertion)
Status of TFCS Production

1) Root Gap : 0.5±0.25mm
2) Misalignment of Welding Root : Within±0.3mm
3) Matching the Splice Plate Side : Within ± 1.3mm
Status of TF Insertion Process
Status of PF5 Production

- Two PF5 Real Double Pancakes (DPs) (DP7 and DP8) windings have been completed

PF5: 2\textsuperscript{nd} DP(DP8) Winding Completed
Status of PF6 Production

- Five PF6 Real DPs (DP5, DP6, DP7, DP8, and DP9) windings have been completed

PF6: 2\textsuperscript{nd} DP(DP8) VPI Completed

PF6: 3\textsuperscript{rd} DP(DP7) VPI Under Preparation
Status of PF1 Production

- Five PF1 Real DP windings have been completed and the 5th DP is underway.
Status of CS Coil Production
In-Vessel Components, Systems in Engineering and Production

W-Divertor, Be First Wall, Shield Blocks, and In-Vessel Coils
Status of Blanket System

Main Functions of ITER Blanket System:

- Exhaust the majority of the plasma power
- Contribute in providing neutron shielding to superconducting coils
- Provide limiting surfaces that define the plasma boundary during startup and shutdown
Status of Blanket FW Manufacturing

Exaggerated shaping

RH access
Status of W-Divertor

Divertor Main Functions:

- Minimize the helium and impurities content in the plasma
- Exhaust part of the plasma thermal power
Status of W-Divertor Manufacturing
Status of In-Vessel Coil System

The in-vessel coils comprise: **3 x 9 picture-framed, ELM coils** (aimed at controlling Edge Localized Modes) and **2 ring, VS coils** (aimed at controlling Vertical Stability).

* PDR finalized successfully.
Status of In-Vessel Coil Conductor

- Round conductor with MgO ceramic insulation
- Coils attachment through brackets
- Unit lengths: up to 70 m
- Weight: 12.4 kg/m
Status of In-Vessel Coil Engineering

- 2 Insulating Breaks
- 2 Pipes (Cooling Supply)
- 2 Jumper Clamps (Power Supply)
- 2 Bellows
- Support Structure

IVC In-situ Joint

Joints (to feeders)

IVC FT & IB
Advancement of Technology R&D

Heating & Current Drive Systems,
Diagnostics, Remote Handling Systems,
and Tritium Systems
Areas of Technology R&D

R&D must be complete in time to enable integration into design and implementation for ITER needs in “Staged Approach”

By internal measures, >85% of design activity is complete: This implies major technology R&D is complete; however, some issues remain and have to be addressed.
ITER Heating Systems

The installed heating power from the 3 systems is 73 MW.
**H&CD in the ITER Research Plan**

**4-Stage Approach:**

- **1st Plasma:** H
- **PFPO-1:** H and $^4$He
- **PFPO-2:** H and $^4$He
- **FPO:** D and DT

<table>
<thead>
<tr>
<th>Year</th>
<th>EC Available, UL 170 GHz, 6.7 MW</th>
<th>Full EC System, 170 (+104-110?) GHz, 20 MW</th>
<th>Full EC System, 170 (+104-110?) GHz, 20 MW</th>
<th>FPO</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>6 m 1st plasma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2026</td>
<td></td>
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<td>2027</td>
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<tr>
<td>2028</td>
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</table>

<table>
<thead>
<tr>
<th>P_{Aux}</th>
<th>6.7 MW</th>
<th>30 MW Non-active phase H, $^4$He</th>
<th>73 MW Active D, DT</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>ECRH</strong></th>
<th><strong>ICRF</strong></th>
<th><strong>NBI</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>170 GHz (+100-110 GHz tbc)</td>
<td>40-55 MHz</td>
<td>870 keV H$^0$, 1 MeV D$^0$</td>
</tr>
<tr>
<td>20 MW (+20 MW upgrade)</td>
<td><strong>20 MW</strong> (+20 MW)</td>
<td><strong>33 MW</strong> (+16.5 MW)</td>
</tr>
<tr>
<td>NTM, ST control, $j(\rho)$ control, EC-assisted startup, modulation &lt; 5 kHz</td>
<td>High fusion gain, ST control, wall cleaning, modulation &lt; 1 kHz</td>
<td>Bulk current drive, rotation, limited modulation</td>
</tr>
<tr>
<td>24 gyrotrons (24x0.8 MW)</td>
<td>2 antennas (2x10 MW)</td>
<td>2 injectors (2x16.5 MW)</td>
</tr>
</tbody>
</table>
Status of ECH PS and RF Sources

Power Supplies: First Factory Acceptance Test has been completed in Nov. 2017; corresponding installation planned for March 2019 (B15);

Gyrotron: Four tubes already in manufacturing or under factory acceptance

RF-DA: first tube’s Factory Acceptance Test started in Oct. 2017; second under manufacturing

JA-DA: first two tube’s manufactured and first Factory Acceptance Test planned in April 2018;

EU-DA: CW prototype being tested in Lausanne for long pulse operation
Status of HNB and DNB Systems

* Front End Components

Heating Neutral Beam Injectors

Diagnostic Neutral Beam Injector

NAS Committee on Strategic Plan for US Burning Plasma Research, 1~2 Feb. 2018
Neutral Beam Test Facility: SPIDER BS

- Beam Dump installed
- Scaffolding installed
- AGPS delivered and installed and tests are underway
- Cooling plant of NBTF
- Plant systems commissioning with CODAS

IC-30: Start of integrated commissioning – end March 2018 (@ RFX)
Neutral Beam Test Facility: MITICA

Beam Source: in procurement

MITICA 1MV Bushing: demonstrated 1MV holding

MITICA vessel supports inside bio shield waiting for vessel installation

MITICA Vessel in manufacturing

1 MV HV Deck

1 MV HV PS system
Status of ICH System

- **Antennas**: EU DA, “Build to print”, IO for the design
- **TL & MS**: US DA, at functional specs
- **RF Sources**: IN DA, at functional specs
- **HVPS**: IN DA, at functional specs (44%), + IO (56%)
Status of Diagnostic System

- 50 different diagnostics identified for different measurement roles
- Just over 100 sub-projects (in PBS55) in all

**PBS55 - Diagnostics**
- A- Magnetics systems
- B- Neutrons systems
- C- Optical systems
- D- Bolometry systems
- E- Spectroscopy systems
- F- Microwave systems
- G- Operational systems

**PBS55-Engineering of:**
- Q- Equatorial Ports
- U- Upper Ports
- L- Lower ports
- NW- Windows
- NE- Electrical Services

**PBS57- IVVS**
**PBS58- PPTF**
Challenges of Diagnostic System

- **Nuclear environment** means we need to mitigate transmutation, radiation damage and thermo-electric effects
- **Target:** zero maintenance (in practice very difficult)
- **Quality requirements are high,** in particular for assembly to the nuclear pressure vessel and vacuum vessel feedthroughs
- **Many interfaces** (machine-diagnostics, diagnostics-diagnostics)
- **Engineering** (remote handling capability, neutron shielding, weight)

- **How are we meeting these?**
  - Staged design, fabrication and installation approach
  - Joint experiments through dedicated International Tokamak Physics Activity Diagnostic Working Group
  - Dedicated R&D and development in the ITER IO-DA Teams
  - Modular design and standardization
Ports for Diagnostic System
ITER Fuel Cycle: Tritium System

Torus loop (DT)

Fueling and Disruption Mitigation

Neutral Beam Loop (D2)

Storage and Delivery System

Isotope Separation System

Detritiation Systems (collect all T as water, recover T from water)

Neutral Beam Vacuum

Vacuum Roughing

Torus Vacuum

Systems: Fueling, Vacuum, Tritium Plant

Torus

D + T → n + He

~1% of feed burns

Stack

Water Detritiation System

Atmosphere Detritiation System

Rooms and enclosures
Status of Fuel Cycle

• **Fuel cycle has unprecedented throughput requirements**
  – Design and safety analysis has advanced
    • Some equipment is already installed, most systems are in preliminary/final design
  – High confidence that systems will work, primary questions relate to number of shots per day that can be supported

• **Vacuum pumping**
  – First torus cryopump manufacturing, testing and delivery completed
  – High-throughput, tritium compatible roughing pump successfully tested

• **Gaseous detritiation system**
  – Verification testing for new, high capacity scrubber column technology completed
  – Recently completed resolution of all major design issues
First Torus/Cryostat Cryo-pump Fabrication

- Cryo-pump Flange
- Assembly of charcoal coated panels
- Thermal Shield Assembly
- Cryo-pump casing preparation for e-beam welding
- Completed Cryo-pump August 2017
- Cryo-pump inlet valve alignment
Due to the massive size of the ITER Tokamak components, as well as the intense neutron flux that will occur during operations, the ITER machine has required the development of cutting-edge robotics and remote handling tools, which will be used in both the assembly and operational phases.
Remote Handling Technology Development

Blanket Remote Handling (Japan)

Overview of the ITER Blanket RH System

Blanket module handling trials using the prototype In-Vessel Transporter (IVT) hosted by the Japanese Domestic Agency in Naka, Japan.

Divertor Remote Handling (EU)

Overview of the ITER divertor remote handling process

* Strong Collaboration (VR, AR, HMI…) with RACE & Industries

Divertor cassette handling trials in the ITER Divertor Test Platform created by the European Domestic Agency in Tampere, Finland.
Technology & Engineering
Breakthroughs and Spinoffs
Multinational Success

- The single largest superconductor procurement in industrial history is completed: An eight-year campaign to produce the superconductors for ITER’s powerful magnet systems

- Six ITER Members—China, Europe, Japan, Korea, Russia and the United States—have been responsible for the production of 200 kilometres (2,800 metric tons) of cable-in-conduit conductors, worth an estimated EUR 610 million.
Considerable technical breakthroughs and spin-offs from the ITER Organization and Domestic Agencies activities can be observed (such as the increase in industrial capacity for the production of superconducting material). The ITER Organization and Domestic Agencies are in the process of identifying all the intellectual property related to these activities.
Summary

ITER focuses on the study of burning plasmas, both medium-pulse (400 s) and long-pulse (>1000 s): enabling scientific research on the next step of fusion science and addressing the risks related to the self-heated plasma state.

- Schedule Optimization of Tokamak Assembly and Tokamak Complex Installation with “under-pinned Critical Deliveries” showed that First Plasma in 2025
- % Complete for FP installed Capital Item Components by end of December: 51.5% complete including IO assembly and installation
- Technologies for ITER have been developed and are in production (for First Plasma) and nearing production (for Post-First Plasma), consistent with the needs of the “Staged Approach”
- “Staged Approach” constitutes a prudent approach to investment protection and risk management: building on the successful demonstration of the previous stages till DT Operation