ITER Engineering Science and Breakthroughs

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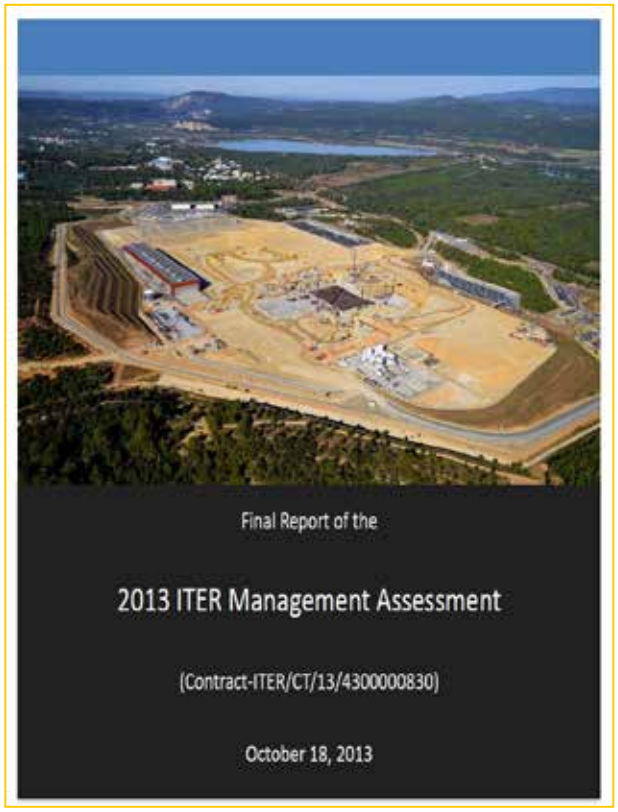
Chief Operating Officer / DDG

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



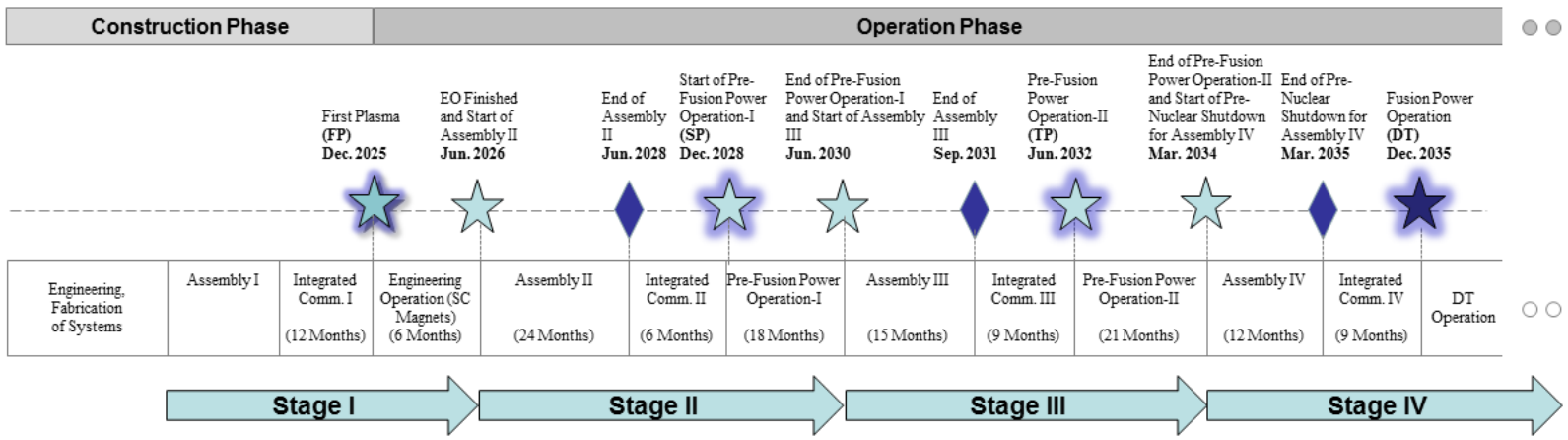
Action Plan 2015: Set clear priorities & timeline for reform

- ✓ 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

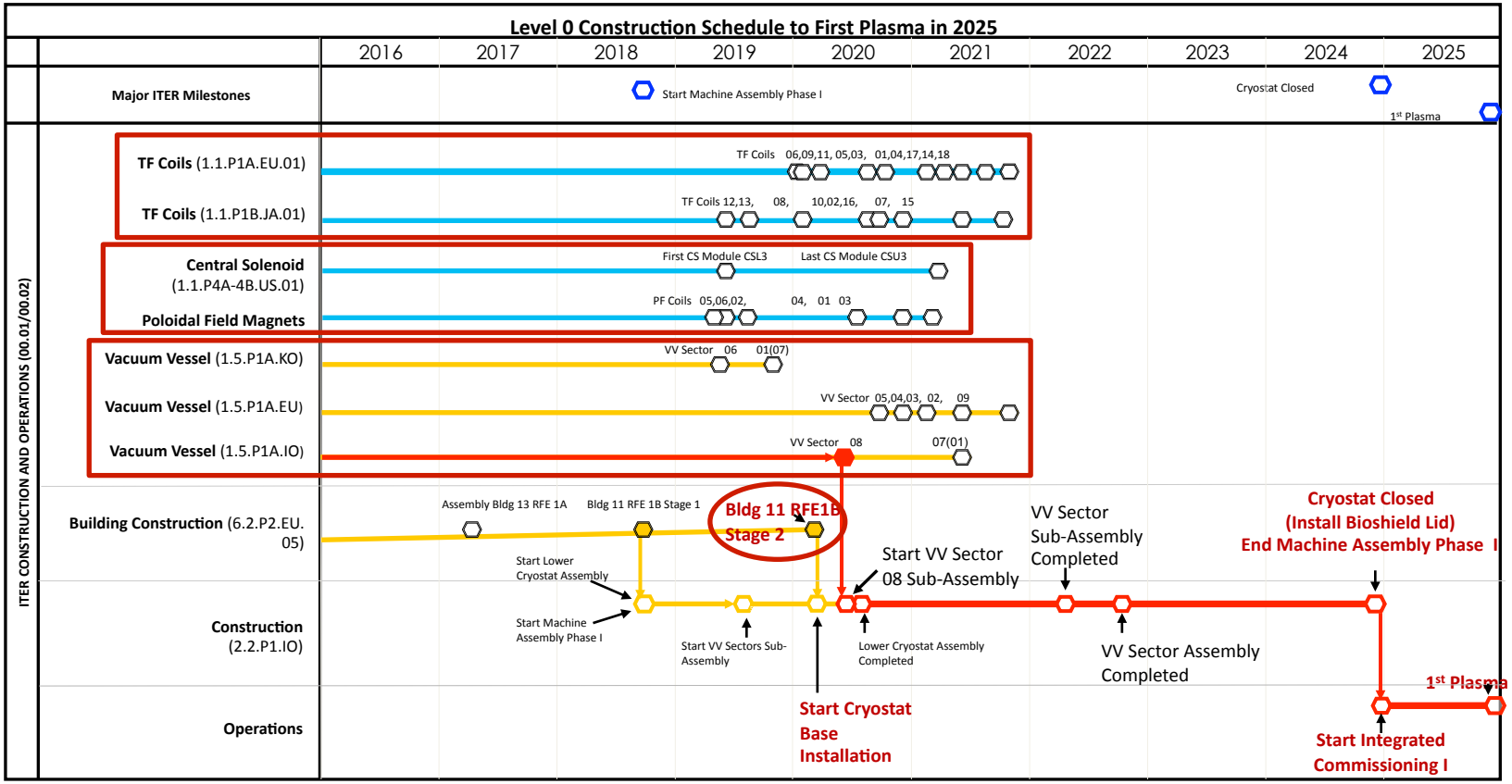
Staged Approach : FP to DT Operation

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

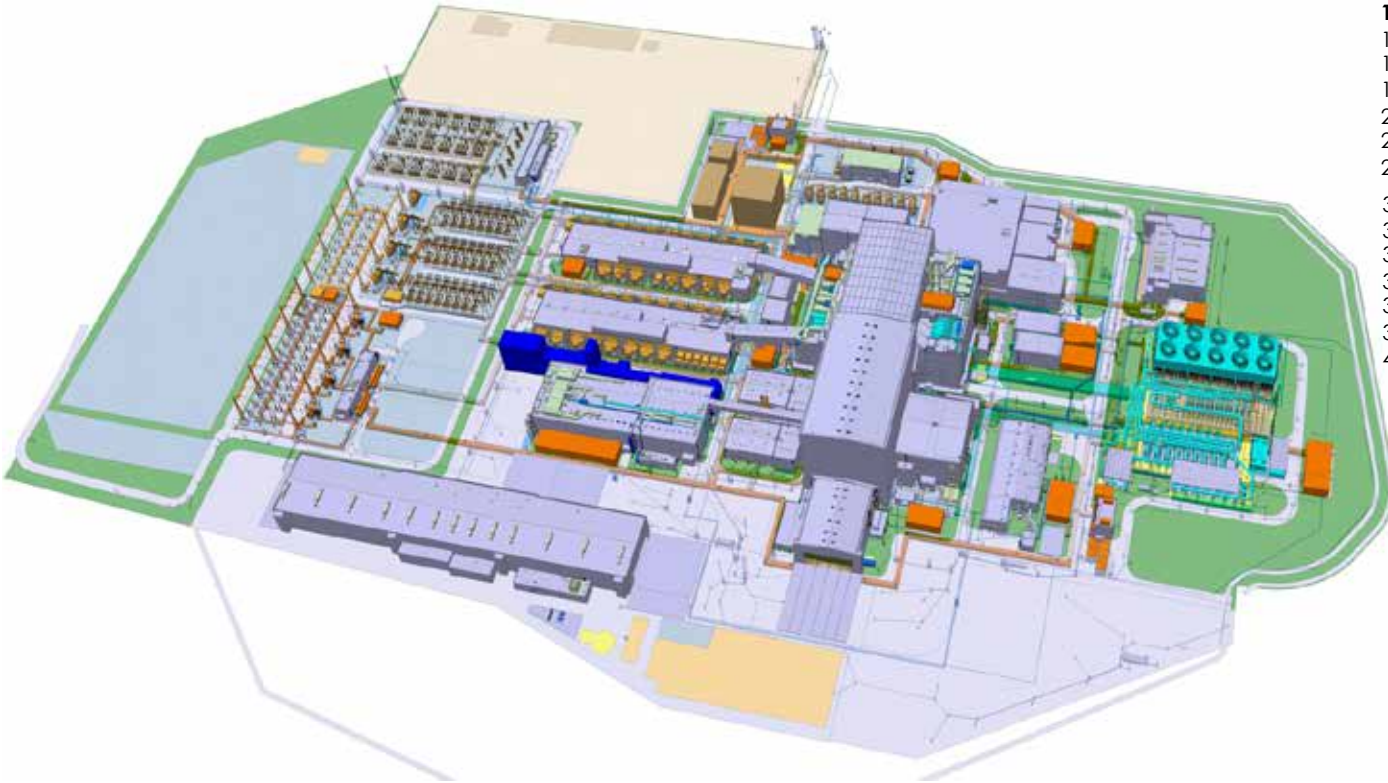
- ✓ Schedule and resource estimates through First Plasma (2025) consistent with Members' budget constraints
- ✓ Adopted **4-stage approach** through Deuterium-Tritium Operation (2035) consistent with Members' financial and technical constraints



Assembly Milestone Schedule to First Plasma



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

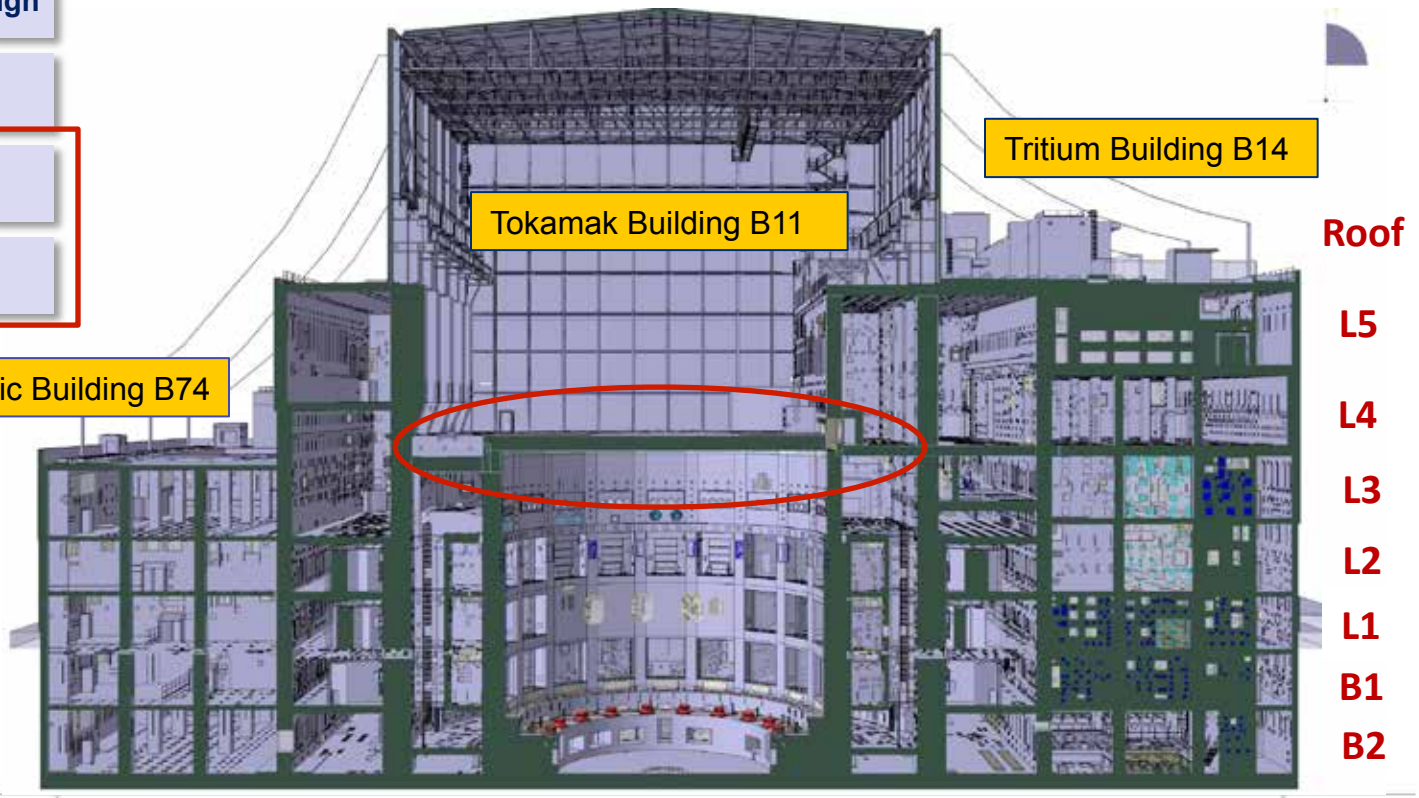
32 MAGNET POWER CONVERSION BUILDING 1
33 MAGNET POWER CONVERSION BUILDING 2
34 NB POWER SUPPLY BUILDING
36 MAIN ALTERNATING CURRENT DISTRIBUTION BLDG
37 NB HIGH VOLTAGE POWER SUPPLY BUILDING
38 REACTIVE POWER CONTROL BUILDING
44 45 EMERGENCY POWER SUPPLY BUILDING

46 47 MEDIUM VOLTAGE DISTRIBUTION BUILDING
49 RTE CONTROL BUILDING
51 CRYOPLANT COMPRESSOR BUILDING
52 CRYOPLANT COLDBOX BUILDING
55 PF COIL FABRICATION BUILDING
56 CRYOSTAT ASSEMBLY BUILDING
57 58 SIC GENERATOR BUILDING

59 60 IP GENERATOR BUILDING
61SITE SERVICES BUILDING
62 HOT WATER BOILERS BUILDING
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

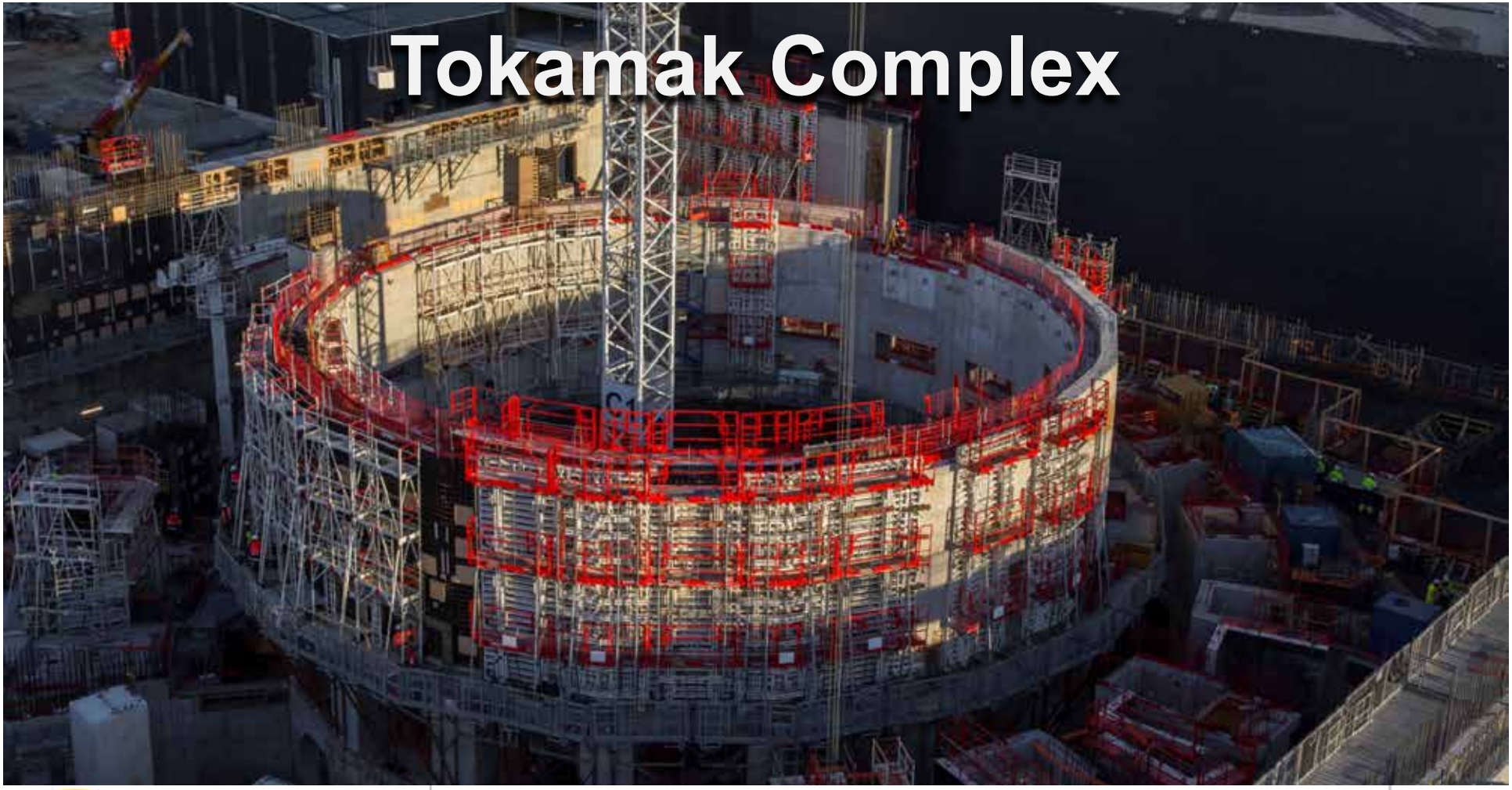


*** Design Interface fully *FROZEN* and no more PCRs affecting Tokamak Building.**

Status of Tokamak Complex Design & Construction

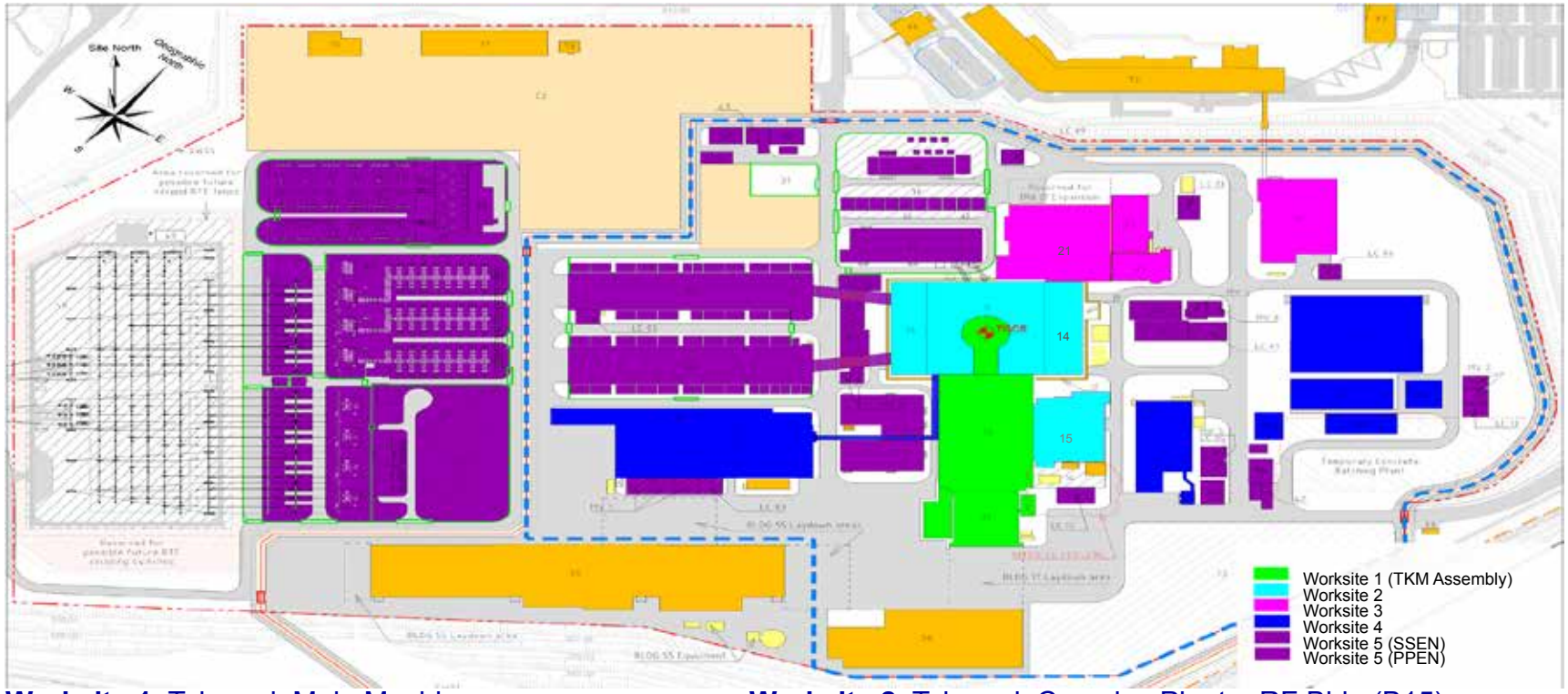
Categorization	Level	Building / MRR Acceptance Reports approval dates	
2 Construction Design	• Level L3	• Bldg. 11, 14, 74:	*August 2017 (last version)*
	• Level L4	• Bldg. 11, 14 :	*August 2016 (1st issue)*
	• Level L5	• Bldg. 11, 14:	*May 2017 (1st issue)*
	• Roof	• Bldg. 11, 14: • Bldg. 74:	*October 2017 (1st issue)* *August 2016 (1st issue)*
3 Execution Design & Construction	• Level B2 Slab	• Bldg. 11, 14, 74:	*September 2017 (Approved by IO)*
	• Level B2 Walls / B2M		
	• Level B1		
	• Level L1		
	• Level L2		
4 As Built Design	• Level B2	• *Bldg. 11, 74:*	*January 2018*

Tokamak Complex



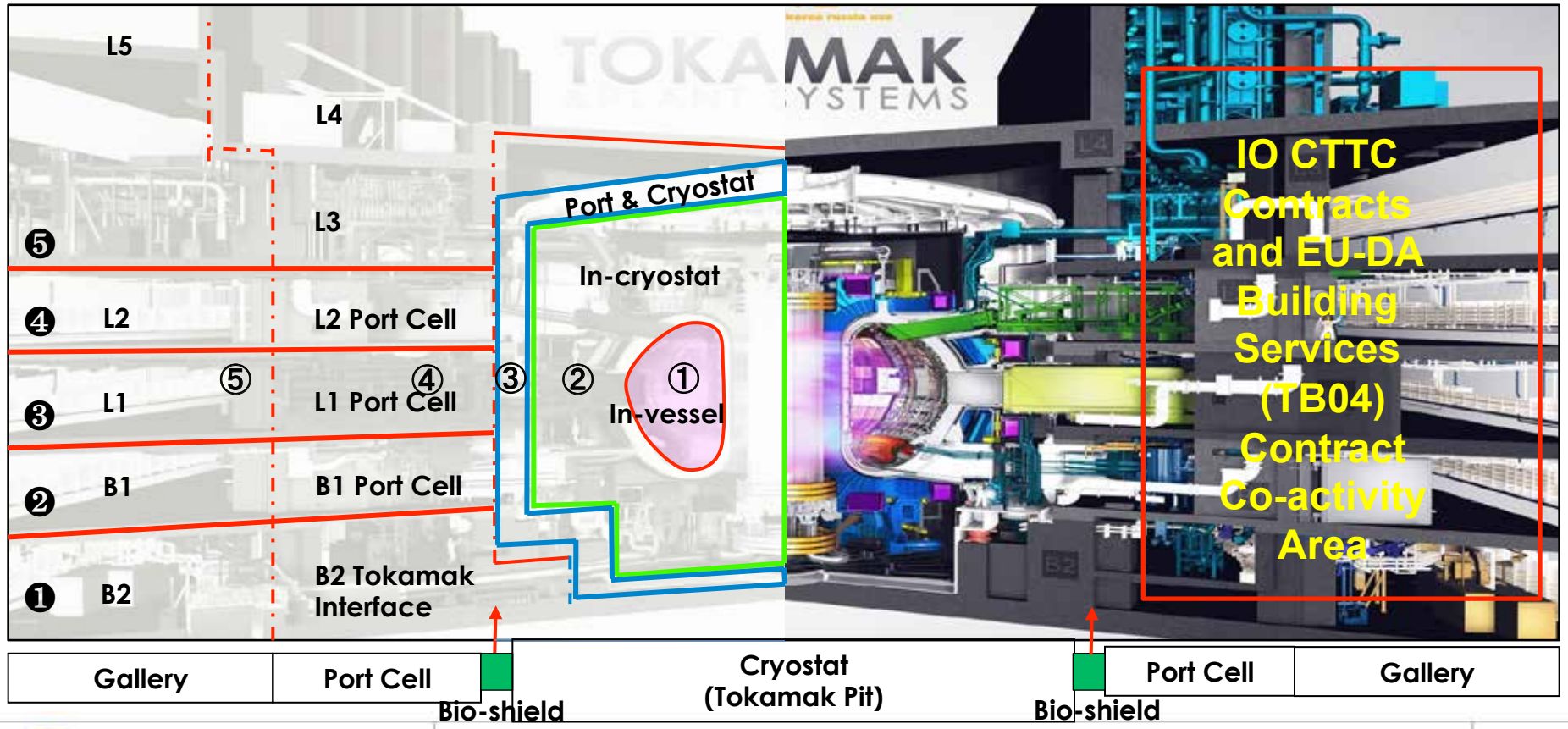
Bioshield Concrete Works Completed

Construction-by-Area Approach (Worksites)

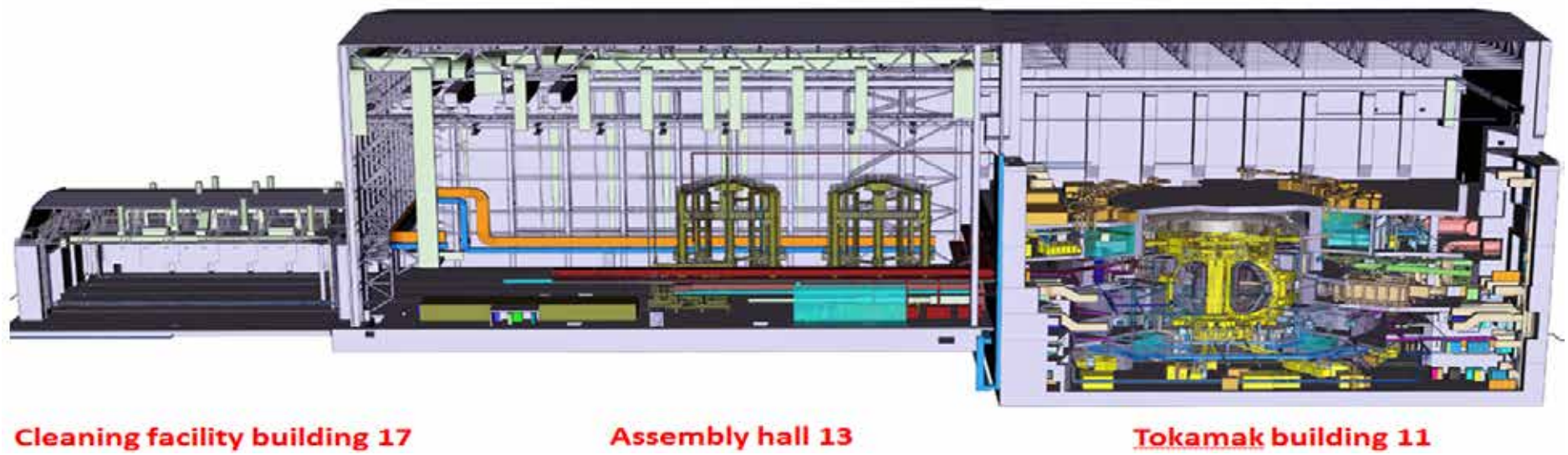


Worksite 1: Tokamak Main Machine,
Worksite 2: Tokamak Complex Plant + RF Bldg.(B15)
Worksite 3: Hot Cell + Rad Waste + Control Buildings,
Worksite 4: Cryogenic Plant + Cooling Station
Worksite 5: Electrical & Power Supply Buildings,

CTTA (Worksite 1) & CTTC (Worksite 2)



Tokamak Assembly Flow (B17 - B13 - B11)



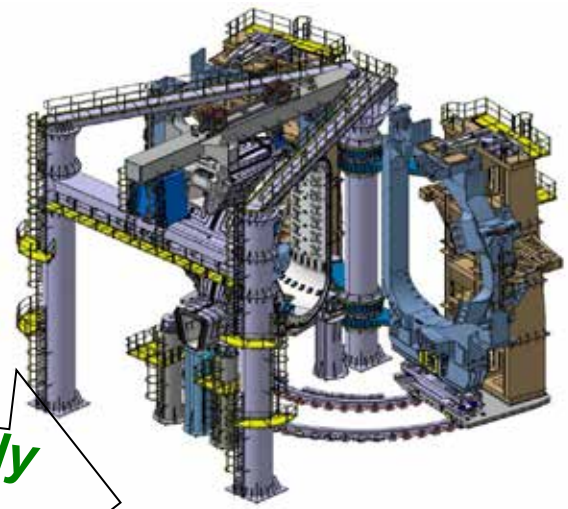
- Introduction of the Tokamak components in Building 17;
- Preparation and sub-assembly of the sectors in Building 13;
- Transport of the sector sub-assemblies via 2x750t crane to the Tokamak Pit;
- Final assembly of the components/sub-assemblies in the Tokamak Pit.

Learning Curve
with Sectors 6 & 7
Sub-assembly

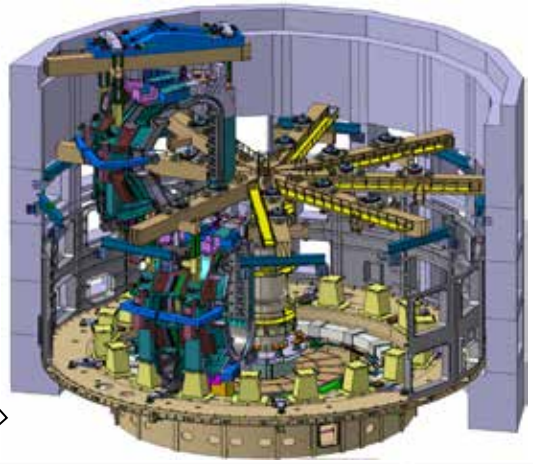
Sector-by-Sector
Assembly (KSTAR,
EAST, JT-60SA) with
Learning Curve by
Sectors 6 & 7

Tokamak Lower In-pit
Installation Activities

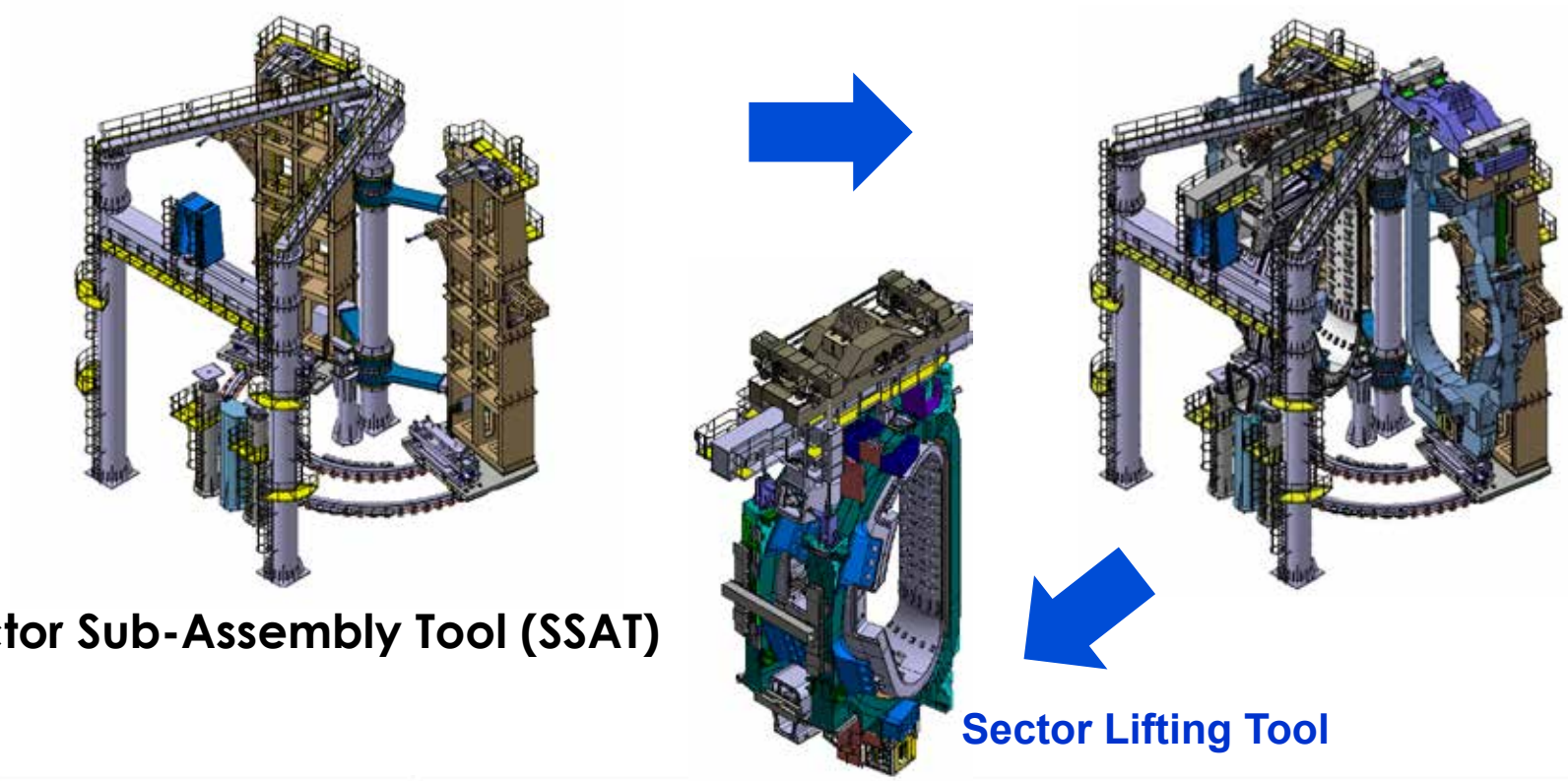
Tokamak Assembly
Hall Activities



Tokamak In-Pit
Installation Activities



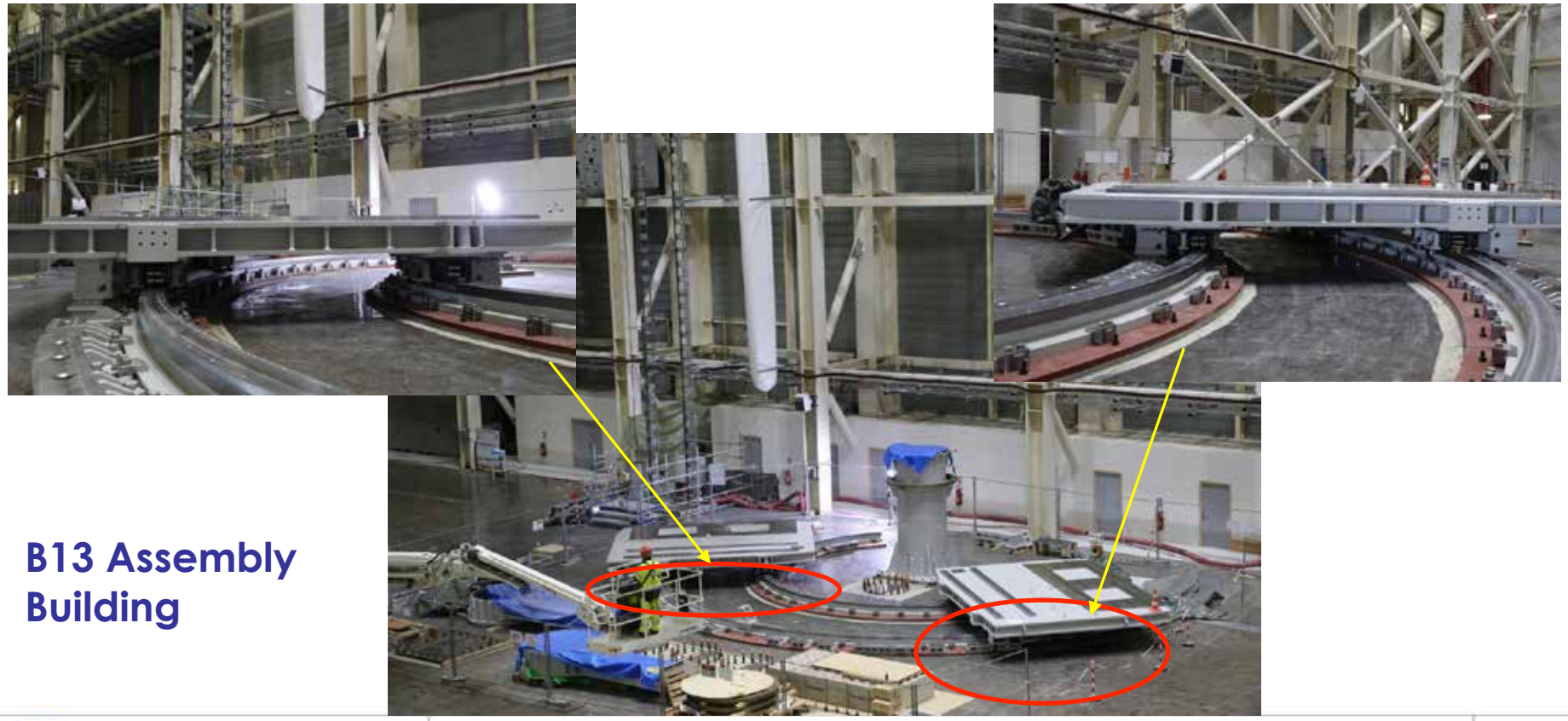
Tokamak Assembly Tools Design



Sector Sub-Assembly Tool (SSAT)

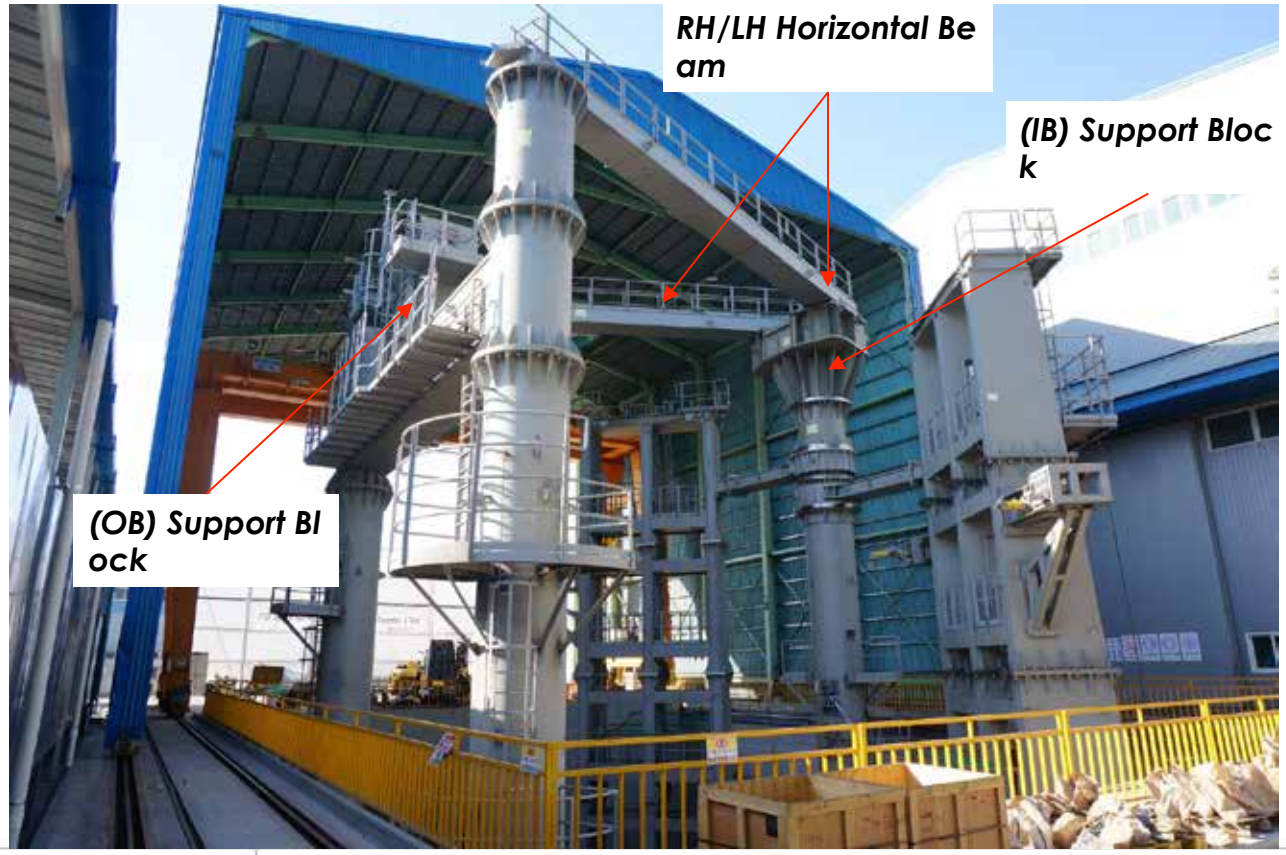
Sector Lifting Tool

Sector Sub-Assembly Tool (SSAT #1)



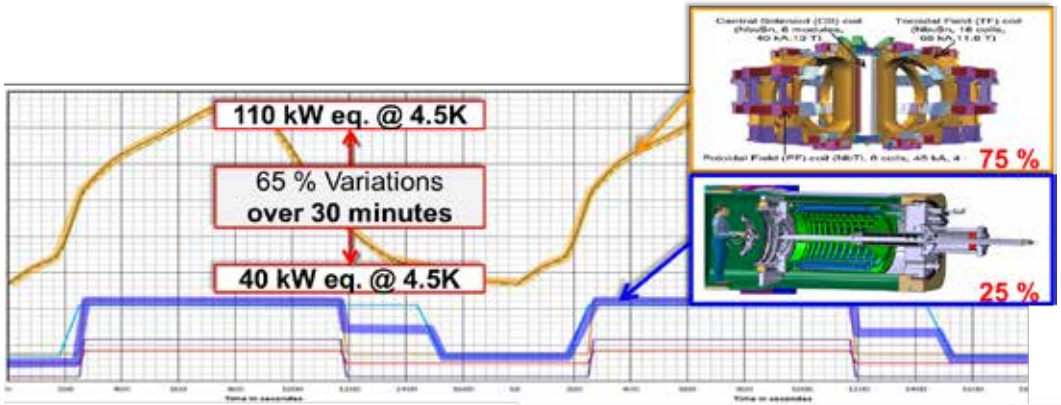
B13 Assembly Building

Sector Sub-Assembly Tool (SSAT #2)

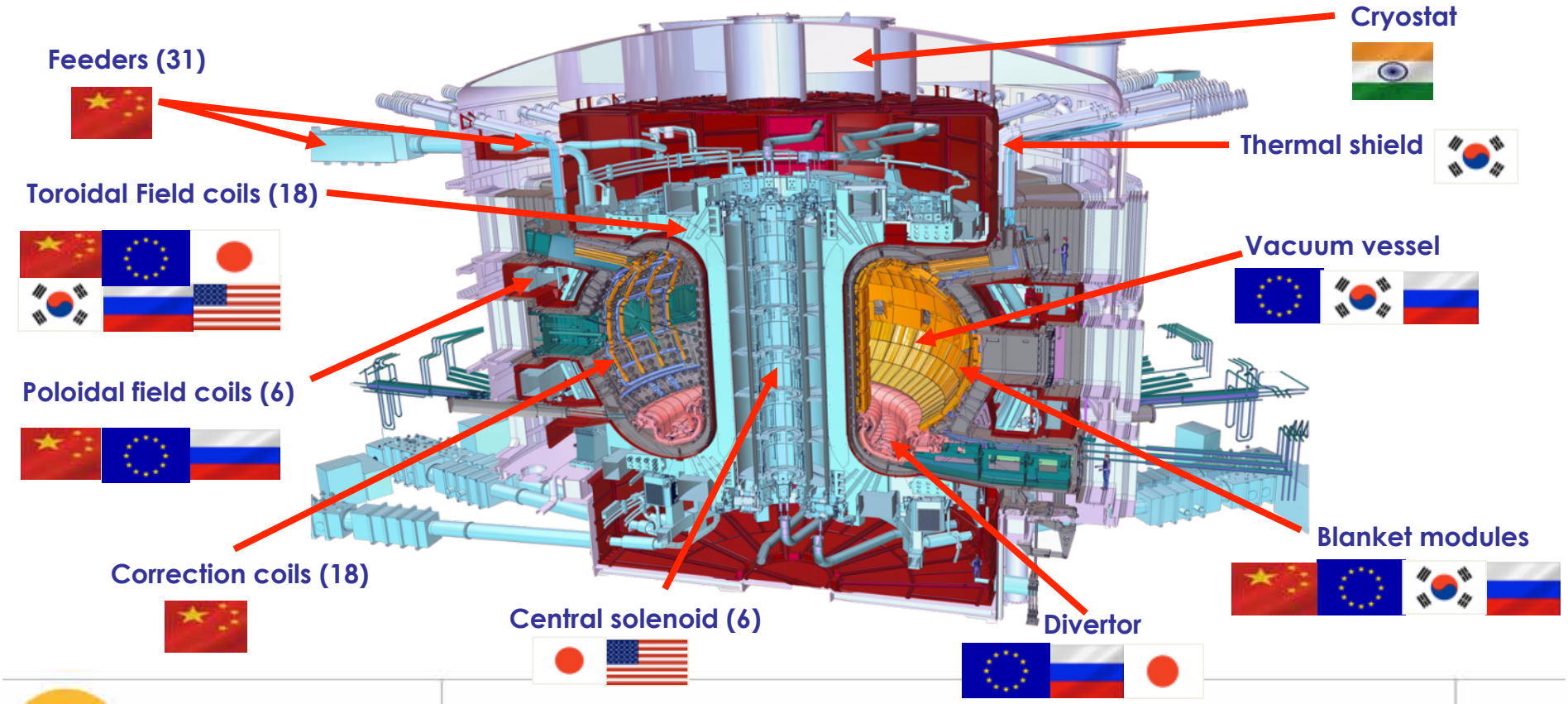


One-of-Kind Plant : Cryogenic System

ITER variable heat loads (overall heat loads)



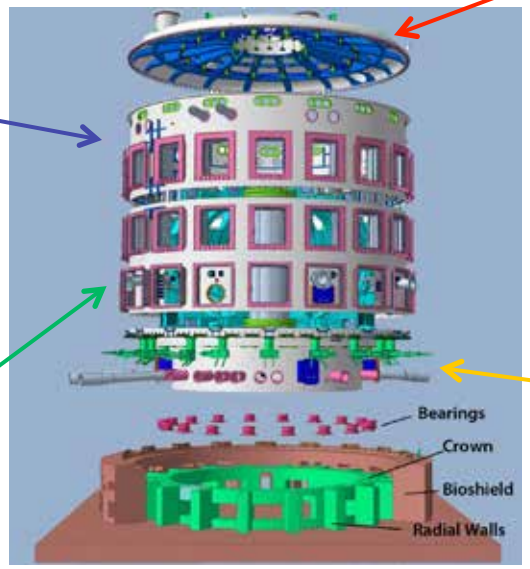
In-kind Procurement Manufacturing



Vessel Systems in Mass Production

Cryostat, Thermal Shields,
and Vacuum Vessel Sectors & Ports

Cryostat in Mass Production



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))*
- **1st application of the RCC-MR 2007 Edition** *(Code & Standard)*
  - 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

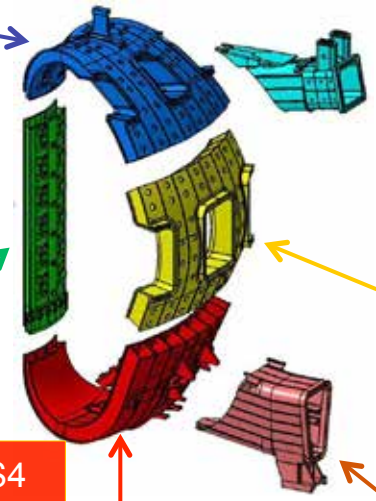
→ All 9 VV sectors are under manufacturing and the first sector (S#6) has been achieved ~77 % of progress

Status of VV Production in KO

PS2

PS1

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



PS4

Upper Port

Delivered from MDT (RF) to HHI (KO)

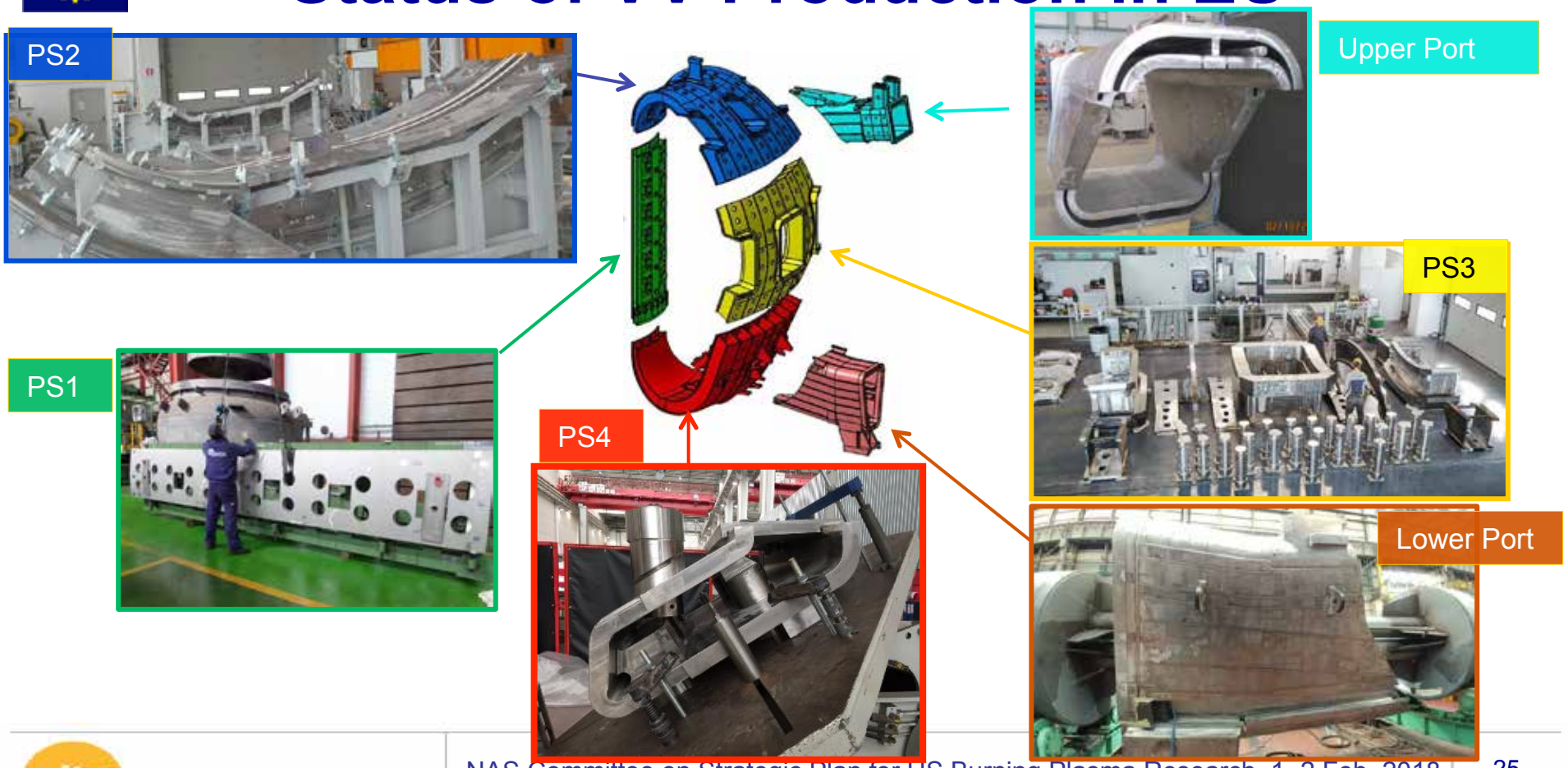
PS3

PS : Poloidal Segment

Lower Port

Manufactured by HHI (KO)

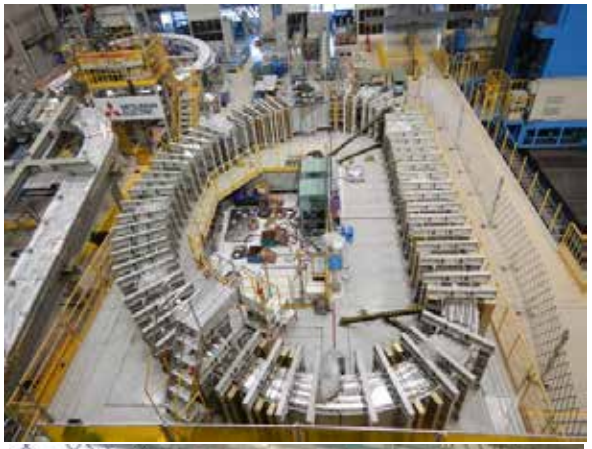
Status of VV Production in EU



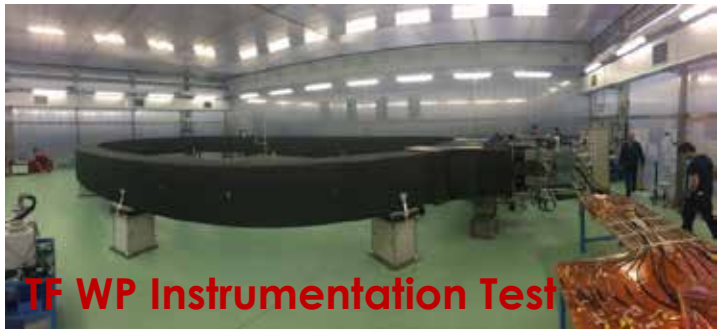
Superconducting Magnets in Full Production

TF Winding Pack, TF Structure, PF Coils, CS Coils, and CC-Coils

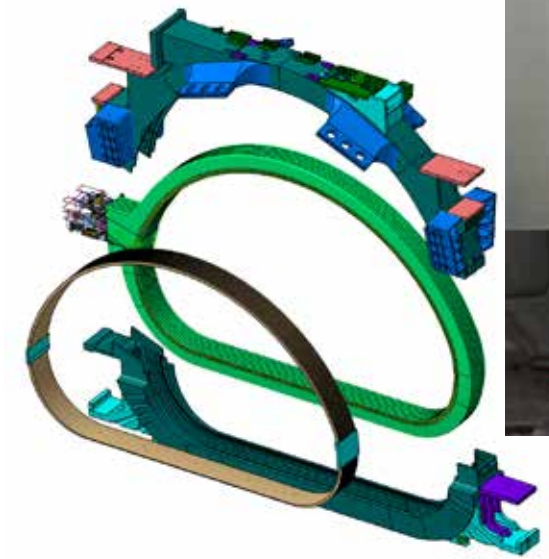
Status of TF WP Production in JA



Status of TF WP Production in EU

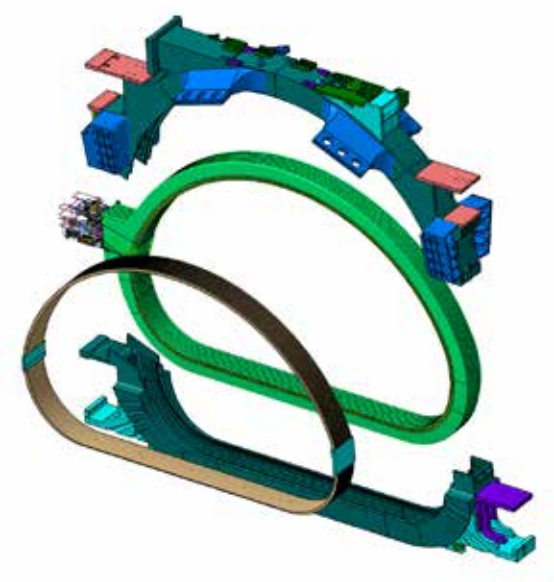


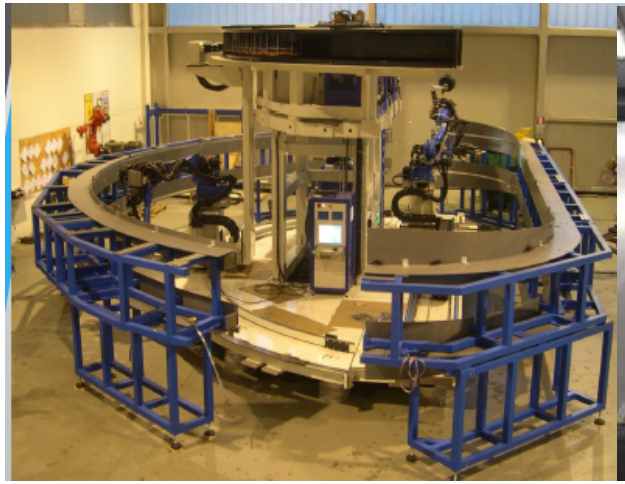
Status of TFCS Production

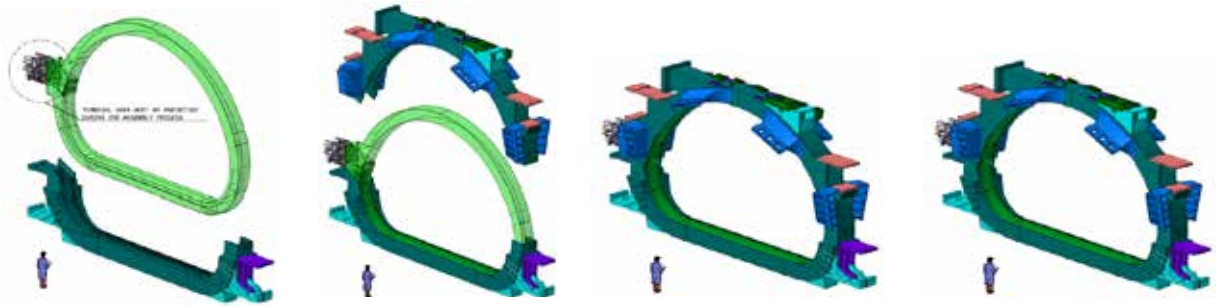


1) Root Gap : 0.5±0.25mm
2) Misalignment of Welding Root : Within±0.3mm
3) Matching the Splice Plate Side : Within ± 1.3mm

Status of TF Insertion Process

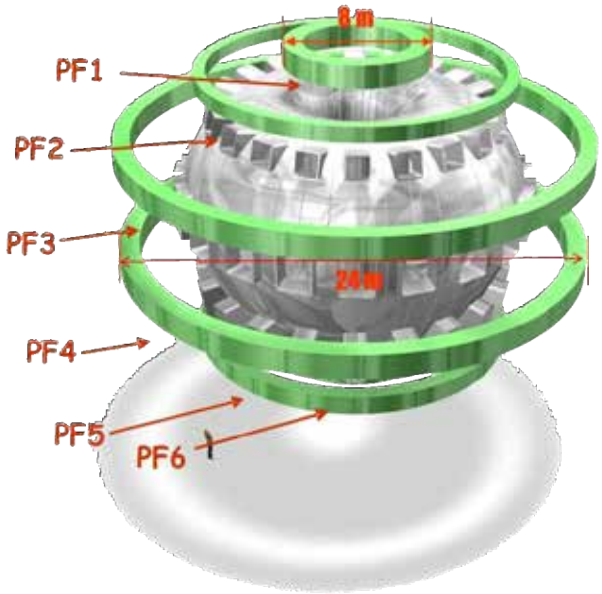






Status of PF5 Production

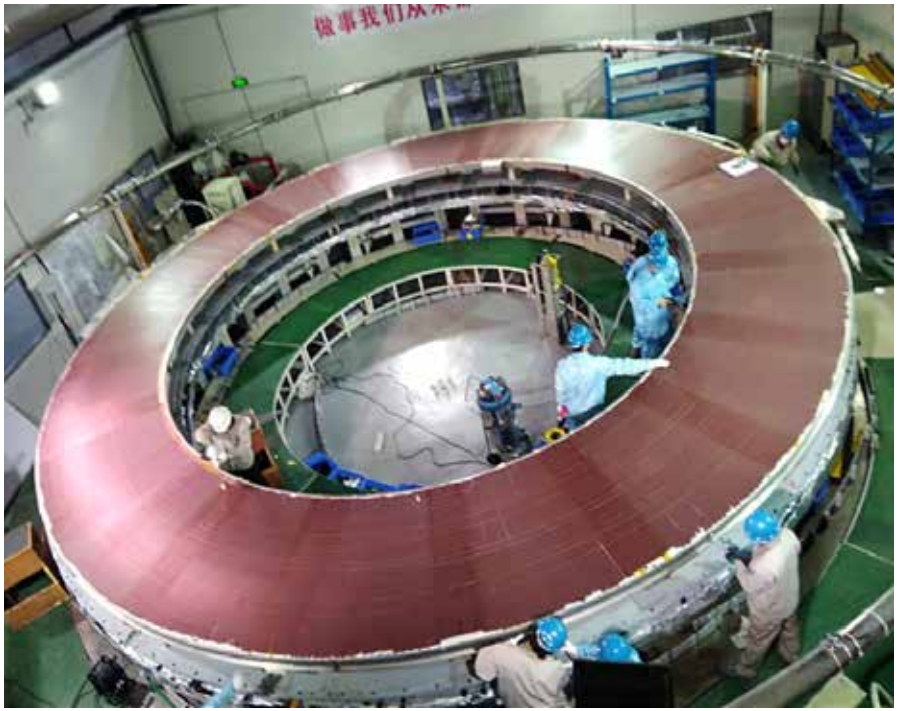
- **Two PF5 Real Double Pancakes (DPs) (DP7 and DP8) windings have been completed**



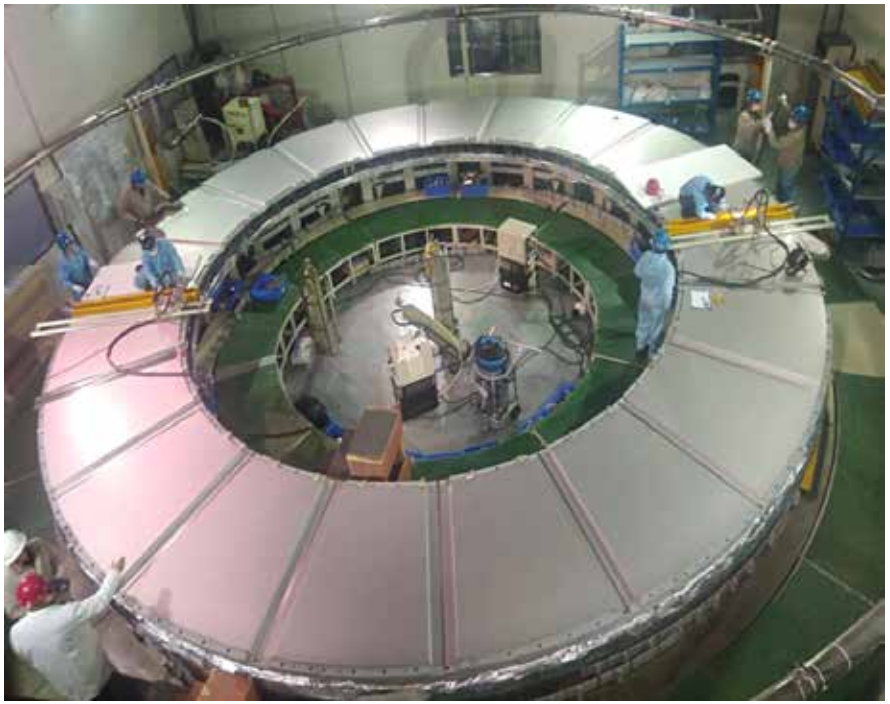
PF5: 2nd DP(DP8) Winding Completed

Status of PF6 Production

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



PF6: 2nd DP(DP8) VPI Completed

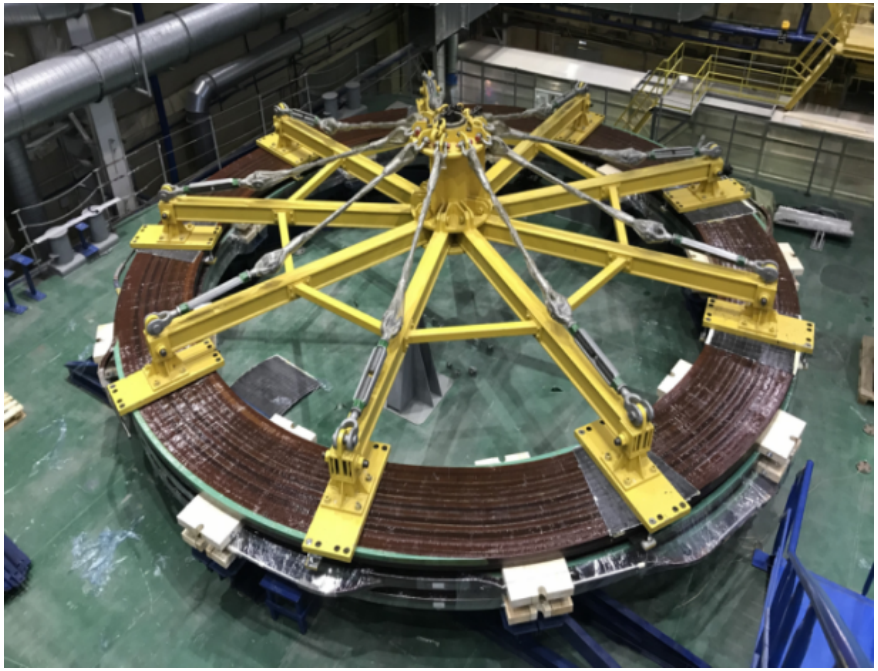


PF6: 3rd DP(DP7) VPI Under Preparation

Status of PF1 Production

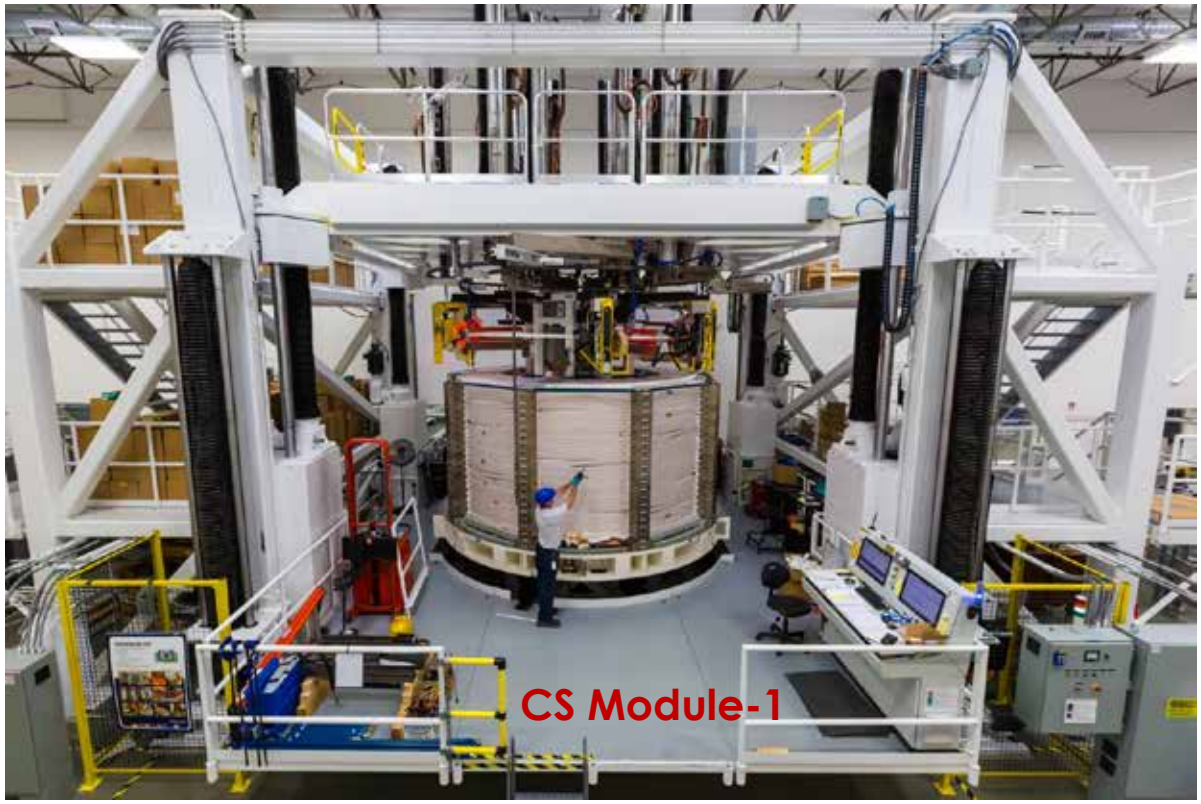
- **Five PF1 Real DP windings have been completed and the 5th DP is underway**

PF1: 5th DP Winding Underway



PF1: 3rd DP VPI Completed

Status of CS Coil Production



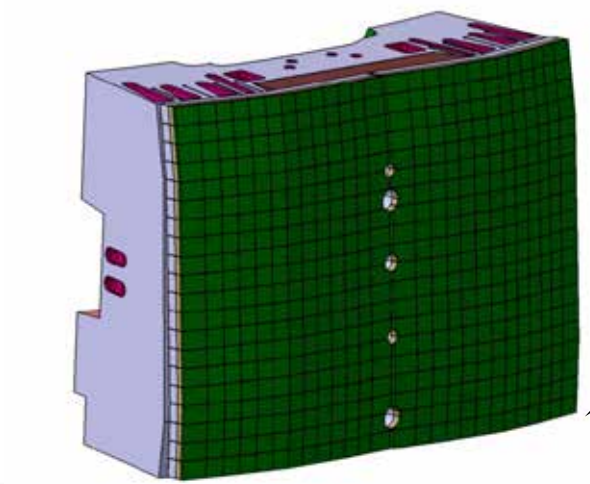
In-Vessel Components, Systems in Engineering and Production

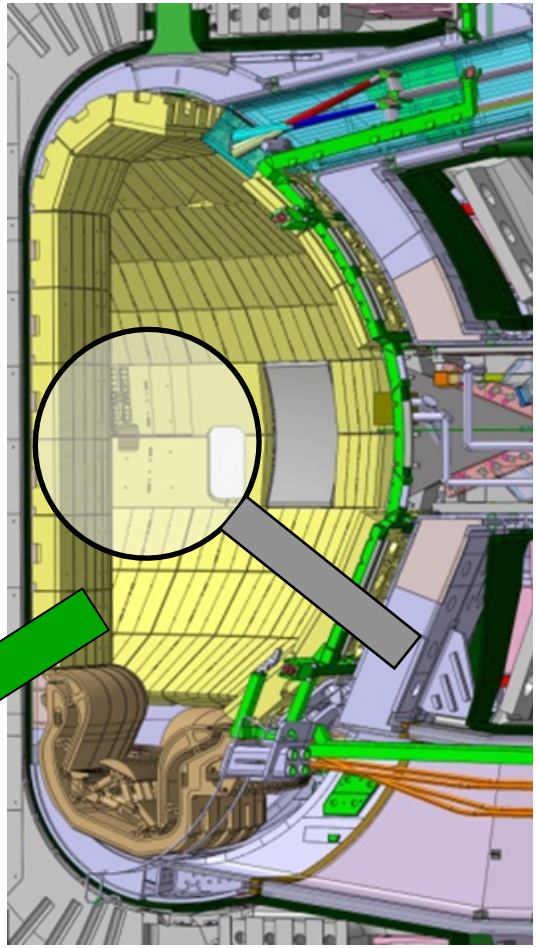
W-Divertor, Be First Wall, Shield Blocks, and In-Vessel Coils

Status of Blanket System

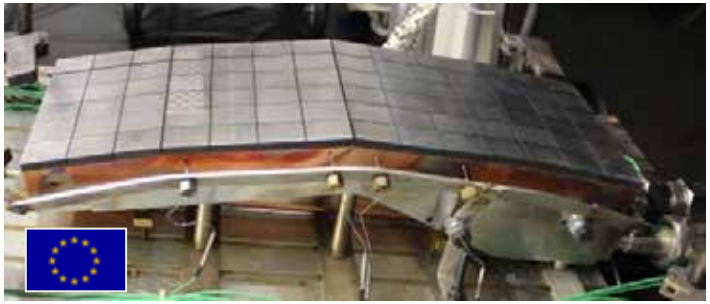
Main Functions of ITER Blanket System:

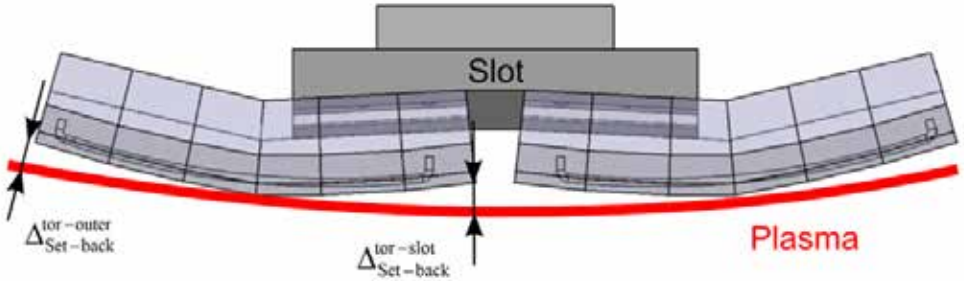
- Exhaust the majority of the plasma power
- Contribute in providing neutron shielding to superconducting coils
- Provide limiting surfaces that define the plasma boundary during startup and shutdown

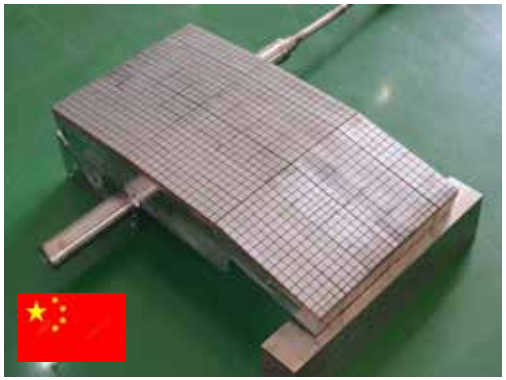


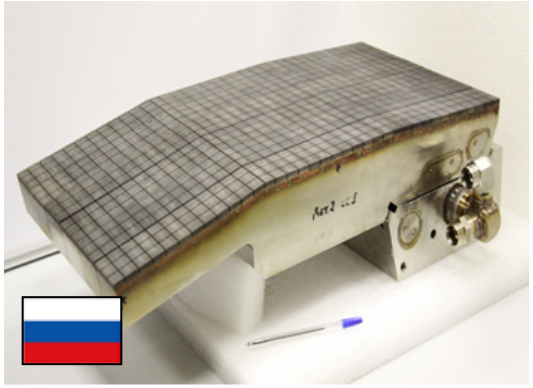


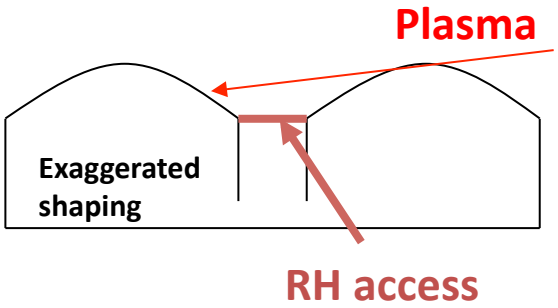
Status of Blanket FW Manufacturing







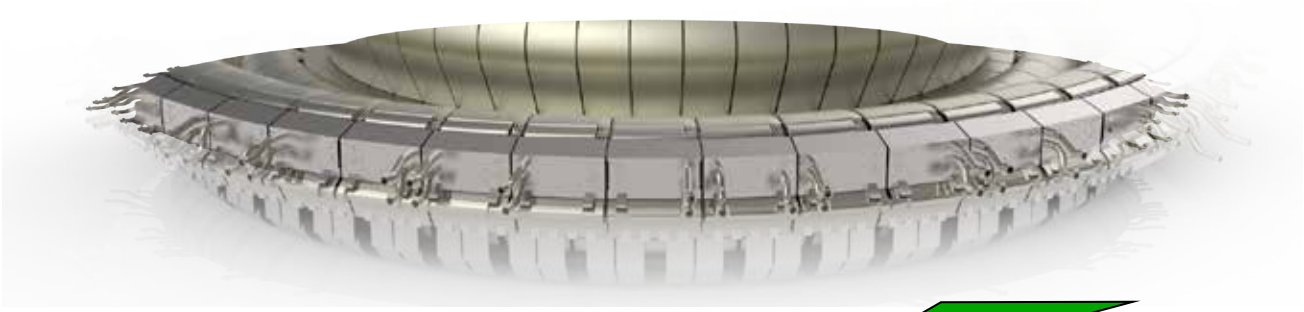


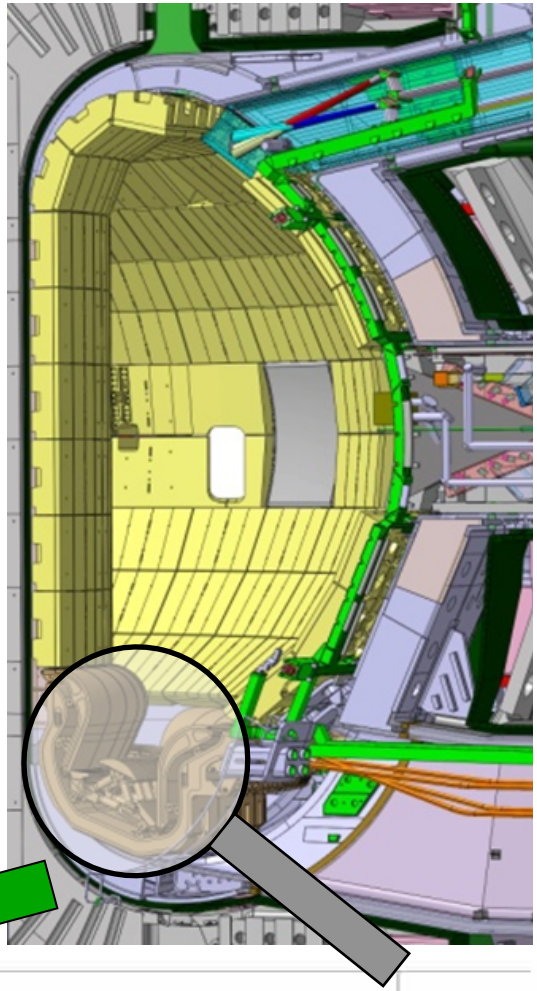


Status of W-Divertor

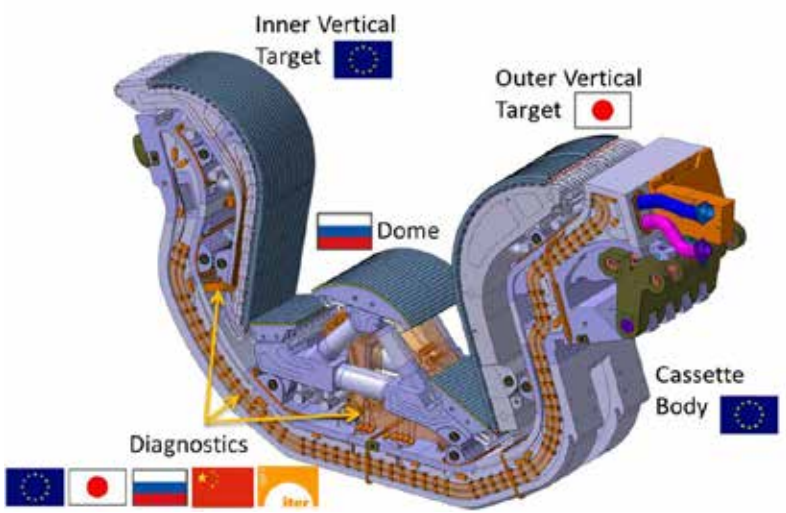
Divertor Main Functions :

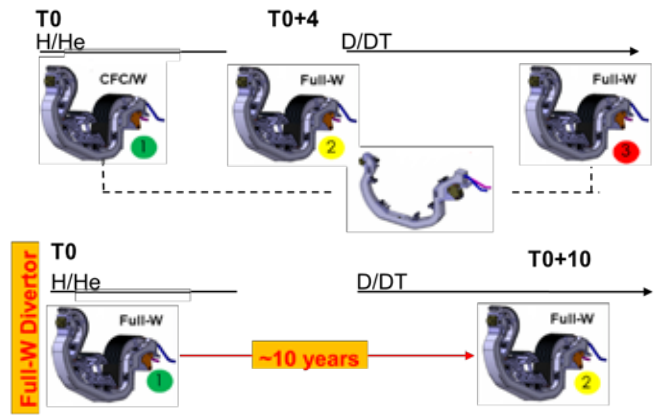
- Minimize the helium and impurities content in the plasma
- Exhaust part of the plasma thermal power

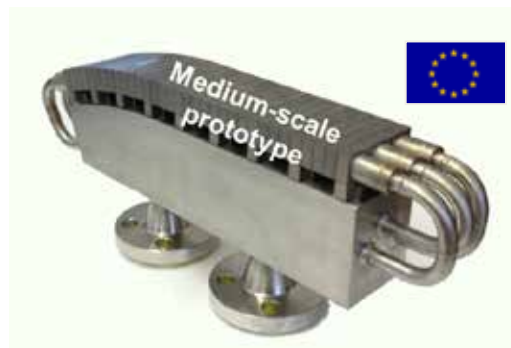


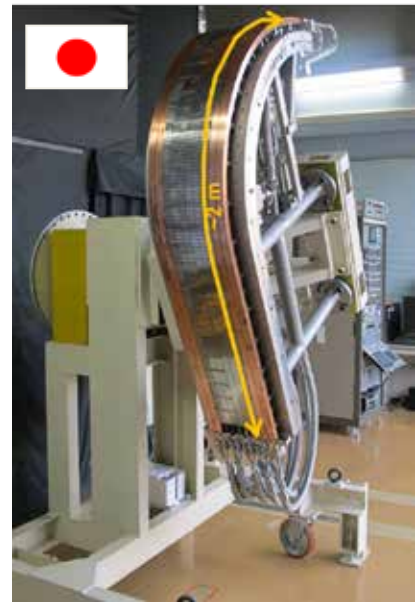


Status of W-Divertor Manufacturing



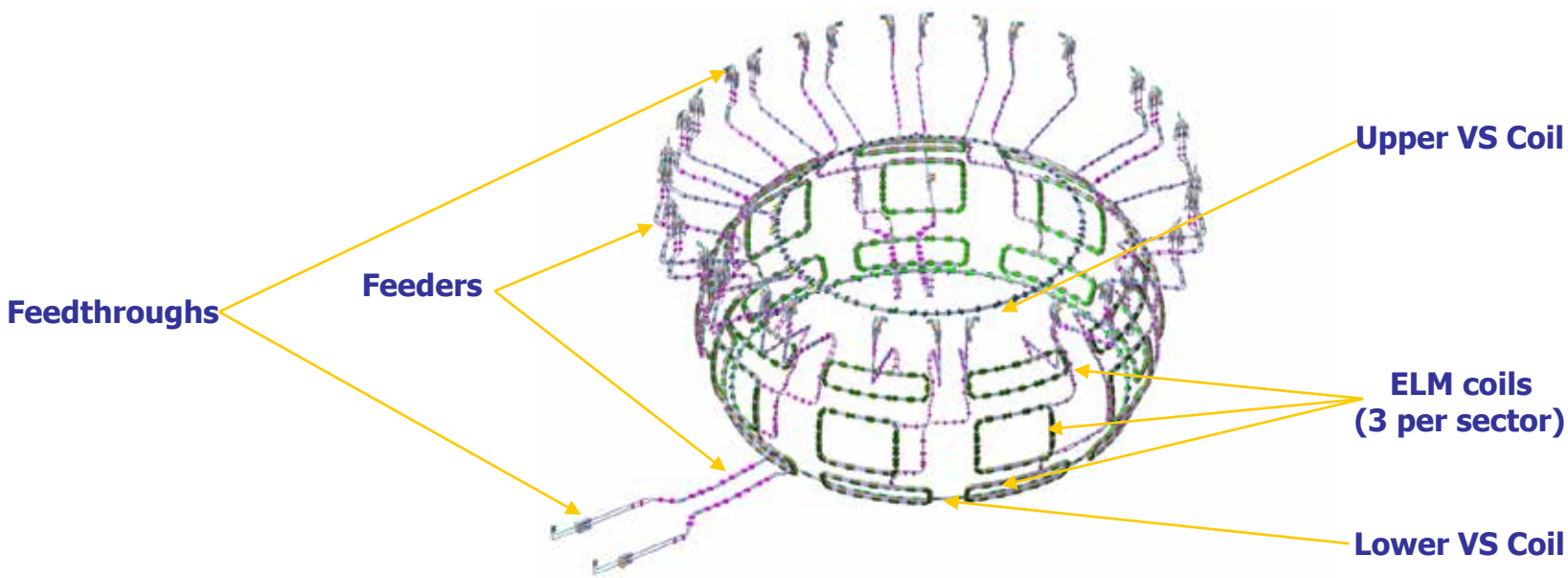






Status of In-Vessel Coil System

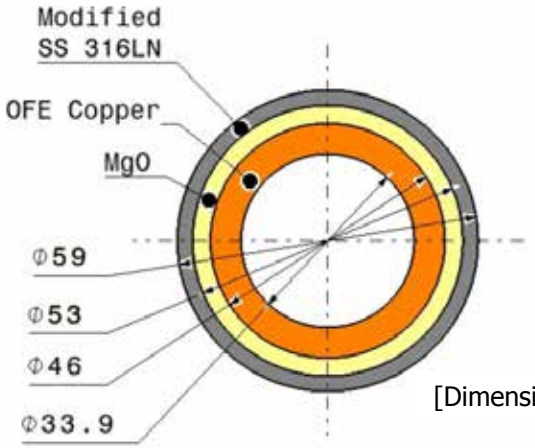
The in-vessel coils comprise: **3 x 9 picture-framed, ELM coils** (aimed at controlling **Edge Localized Modes)** and **2 ring, VS coils** (aimed at controlling **Vertical Stability).**



*** PDR finalized successfully.**

Status of In-Vessel Coil Conductor

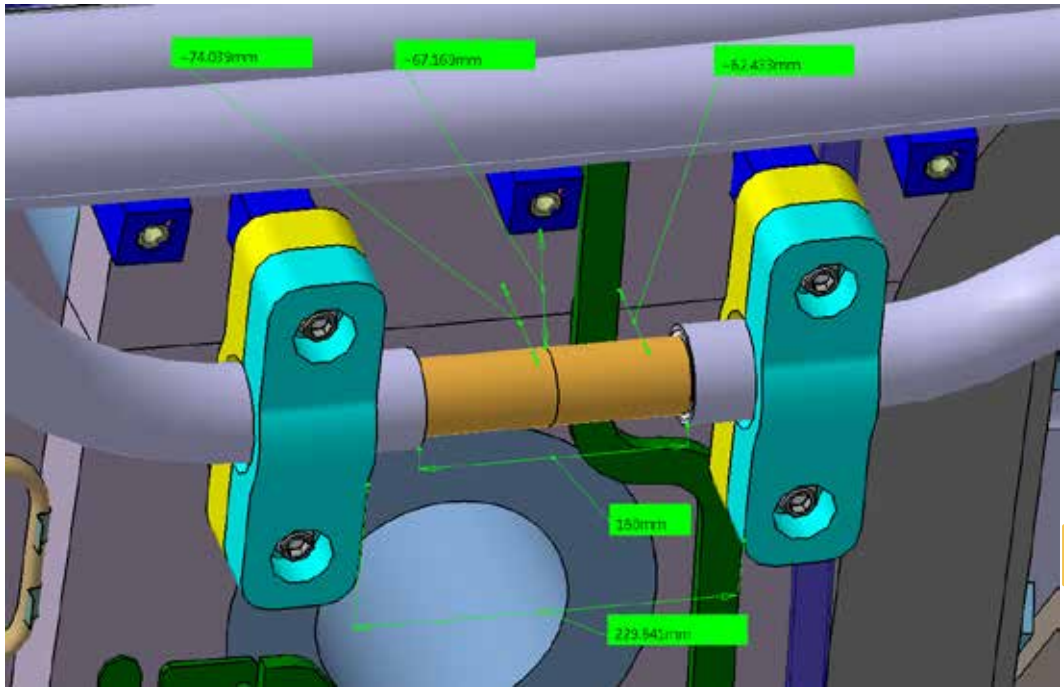
- Round conductor with MgO ceramic insulation
- Coils attachment through brackets
- Unit lengths: up to 70 m
- Weight: 12.4 kg/m



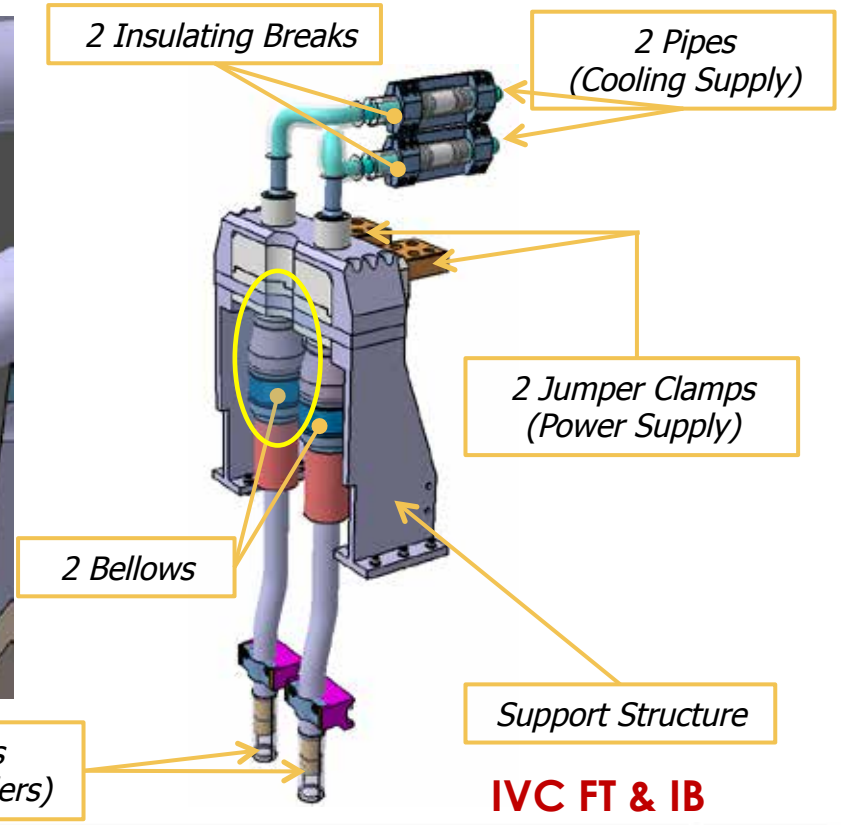
[Dimensions in mm]

[ASIPP]

Status of In-Vessel Coil Engineering



IVC In-situ Joint



IVC FT & IB

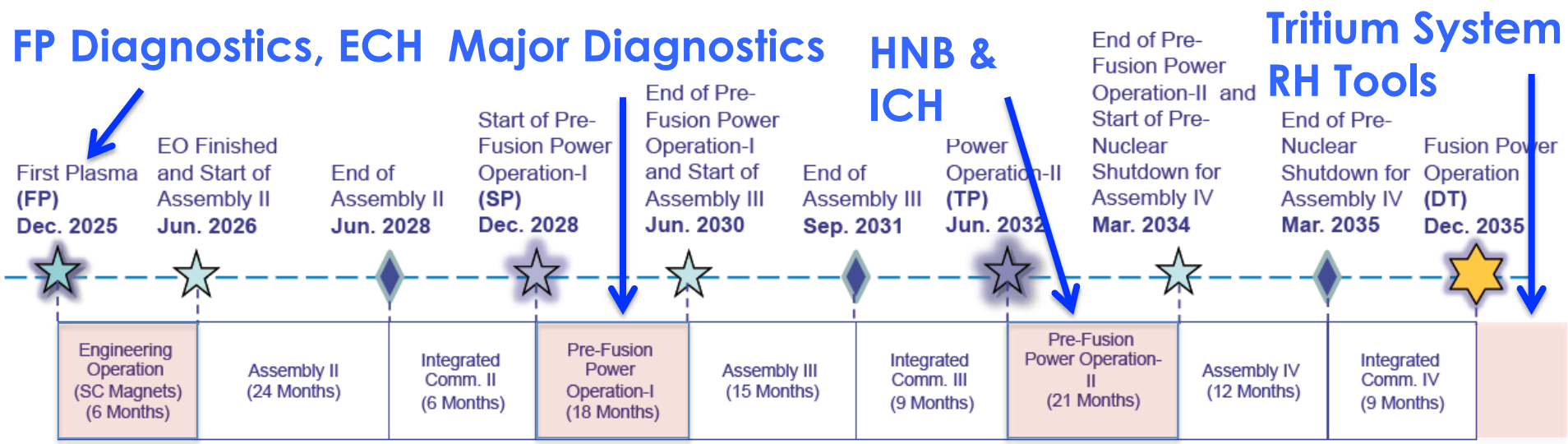
Advancement of Technology R&D

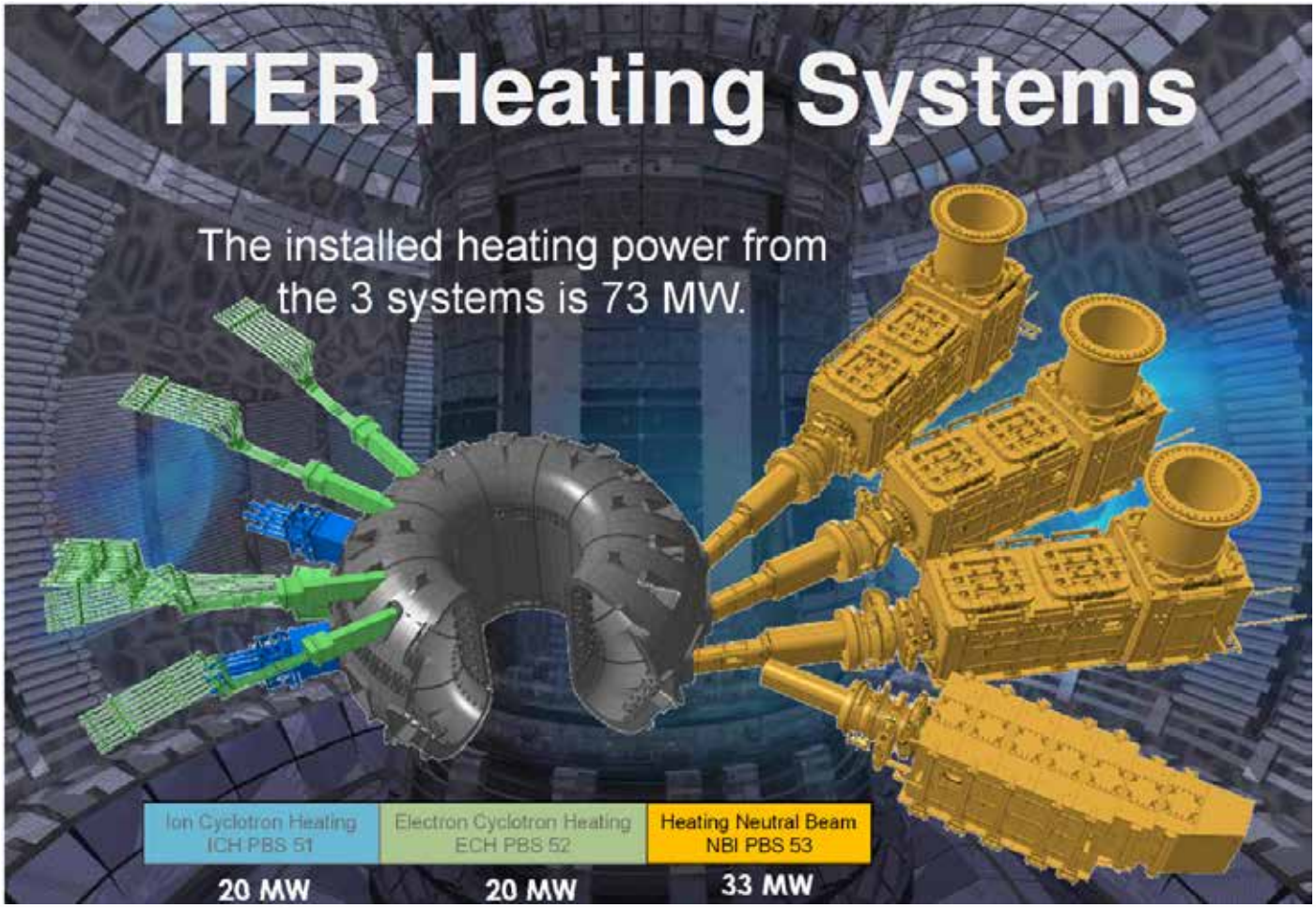
Heating & Current Drive Systems, Diagnostics, Remote Handling Systems, and Tritium Systems

Areas of Technology R&D

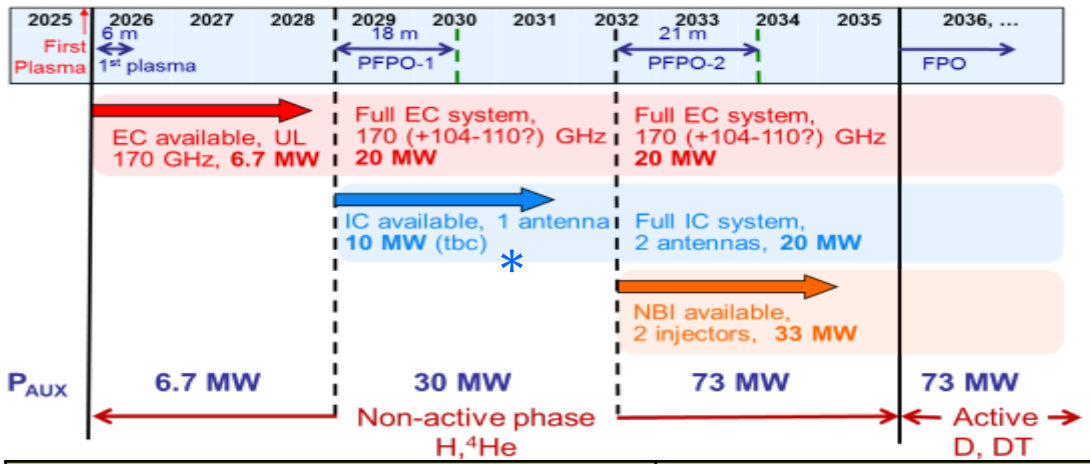
R&D must be complete in time to enable integration into design and implementation for ITER needs in "Staged Approach"

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.
Ion Cyclotron Heating ICH PBS 51
Electron Cyclotron Heating ECH PBS 52
Heating Neutral Beam NBI PBS 53
20 MW
20 MW
33 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

ECRH	ICRF	NBI
170 GHz (+100-110 GHz tbc)	40-55 MHz	870 keV H^0, 1 MeV D^0
20 MW (+20 MW upgrade)	**20 MW** (+20 MW)	**33 MW** (+16.5 MW)
NTM, ST control, $j(\rho)$ control, EC-assisted startup, modulation < 5 kHz	High fusion gain, ST control, wall cleaning, modulation < 1 kHz	Bulk current drive, rotation, limited modulation
24 gyrotrons (24x0.8 MW)	2 antennas (2x10 MW)	2 injectors (2x16.5 MW)

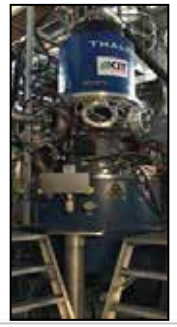
Status of ECH PS and RF Sources

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

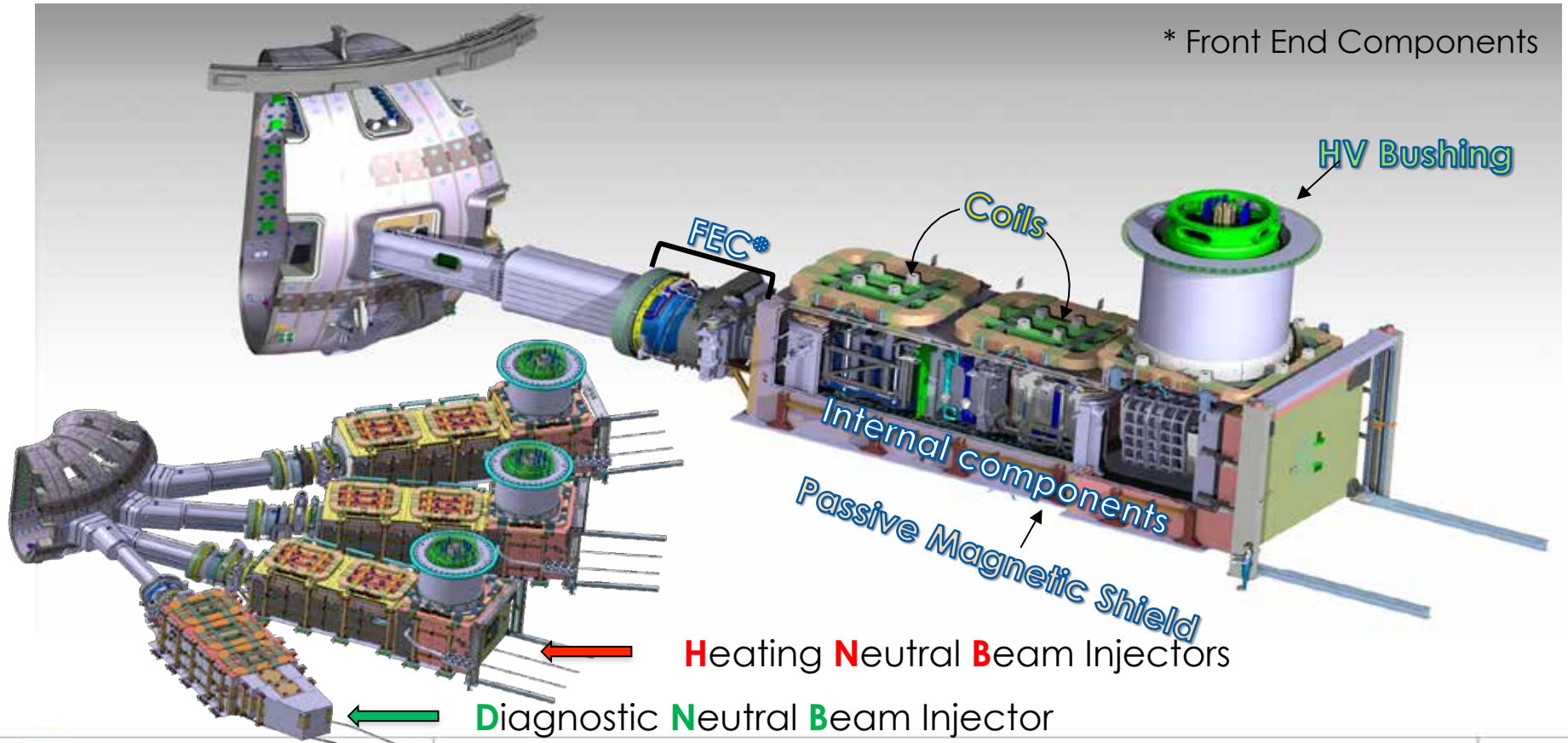
RF-DA: first tube's Factory Acceptance Test started in Oct. 2017; second under manufacturing

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



Neutral Beam Test Facility : SPIDER BS

SPIDER Beam Source : installation phase

Beam Dump installed

Scaffolding installed

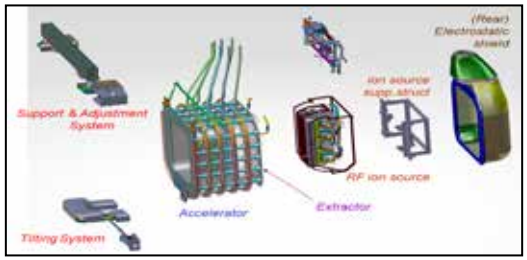
Cooling plant of NBTF

AGPS delivered and installed and tests are underway

Plant systems commissioning with CODAS

IC-30: Start of integrated commissioning – end March 2018 (@ RFX)

Neutral Beam Test Facility : MITICA



Beam Source: in procurement

1 MV HV Deck

1 MV HV PS system

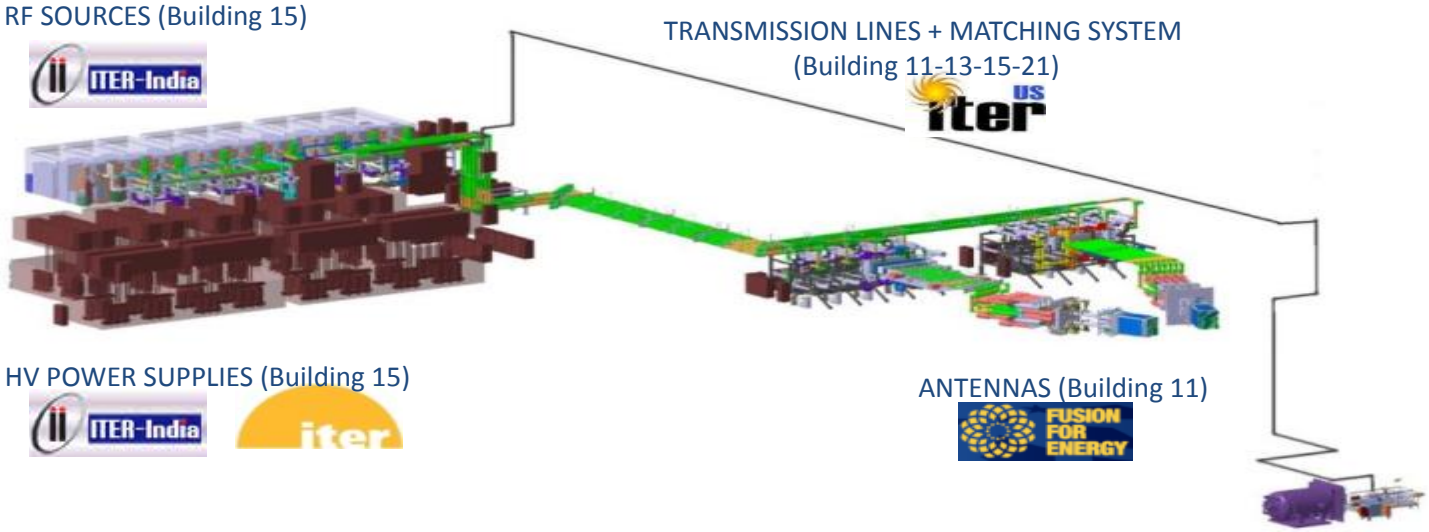
MITICA 1MV Bushing: demonstrated 1MV holding

MITICA vessel supports inside bio shield waiting for vessel installation

MITICA Vessel in manufacturing

FUSION FOR ENERGY iter CONSORZIO REX ITER JAPAN ITER-India

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

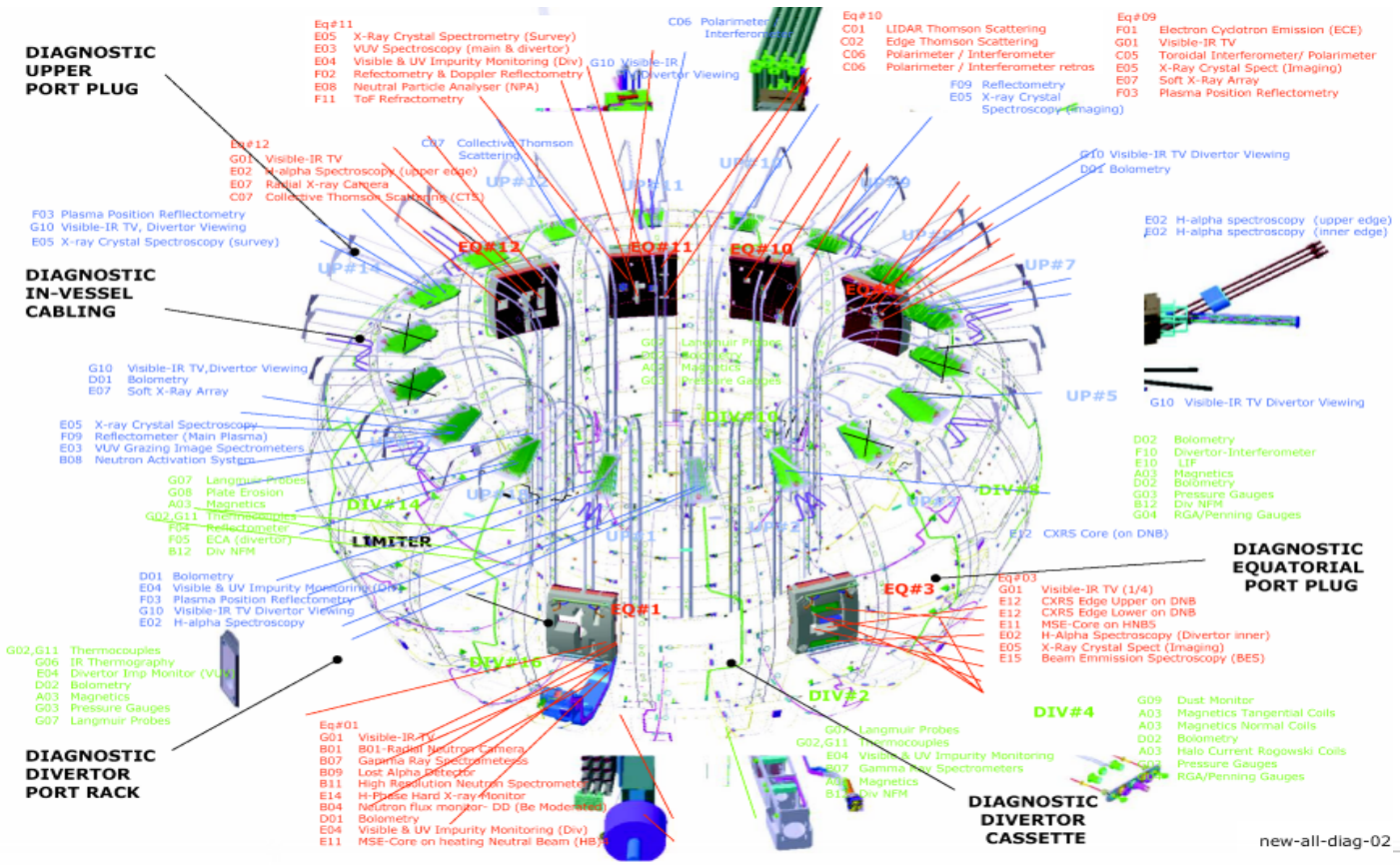
PBS57- IVVS
PBS58- PPTF

Challenges of Diagnostic System

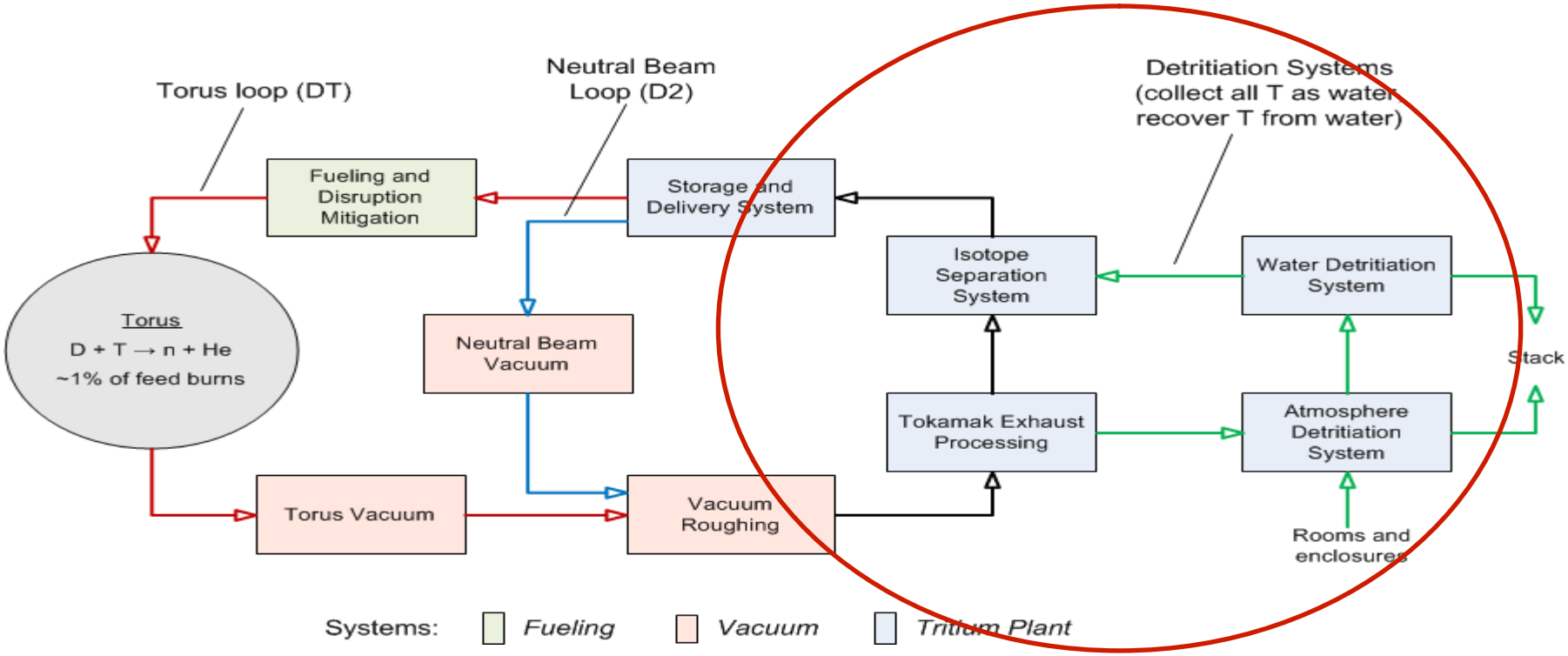
- **Nuclear environment** means we need to mitigate transmutation, radiation damage and thermo-electric effects
- Target: **zero maintenance** (in practice very difficult)
- **Quality requirements are high**, in particular for assembly to the nuclear pressure vessel and vacuum vessel feedthroughs
- **Many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



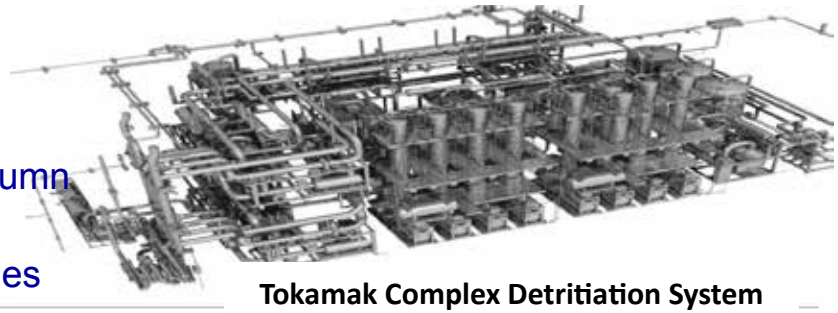
ITER Fuel Cycle : Tritium System



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

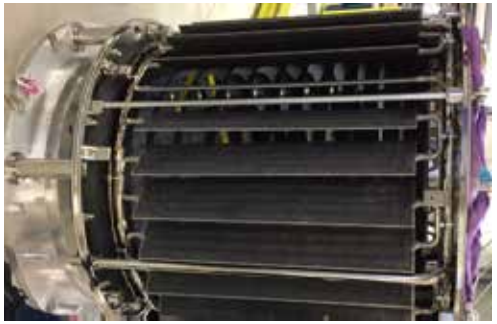
Receipt of Torus Cryopump



Tokamak Complex Detritiation System

First Torus/Cryostat Cryo-pump Fabrication

Cryo-pump Flange



Assembly of charcoal coated panels

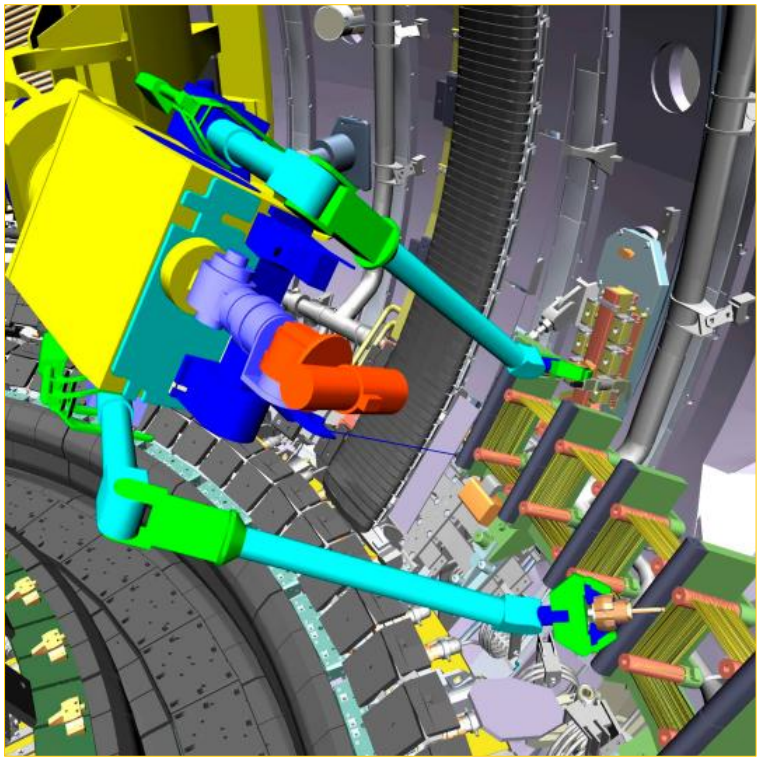
Thermal Shield Assembly

Cryo-pump casing preparation for e-beam welding

Completed Cryo-pump August 2017

Cryo-pump inlet valve alignment

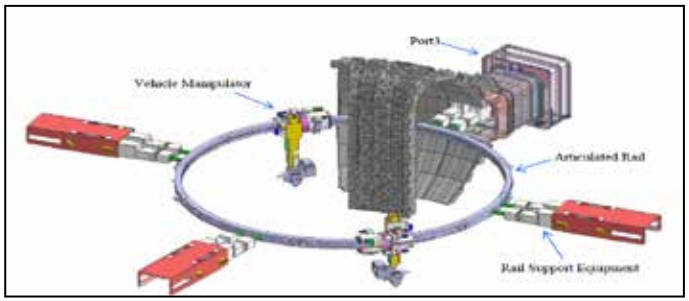
Advanced Robotics and Remote Handling



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.

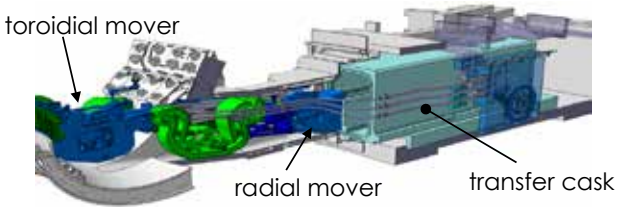
Remote Handling Technology Development

Blanket Remote Handling (Japan)



Overview of the ITER Blanket RH System

Divertor Remote Handling (EU)



Overview of the ITER divertor remote handling process

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

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

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.**

ITER Technologies are being developed, demonstrated, are documented, and will be available for the Members' Fusion Programs

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** <u>including</u> **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