

Progress in ITER Construction and Strategy towards the Operations Phase



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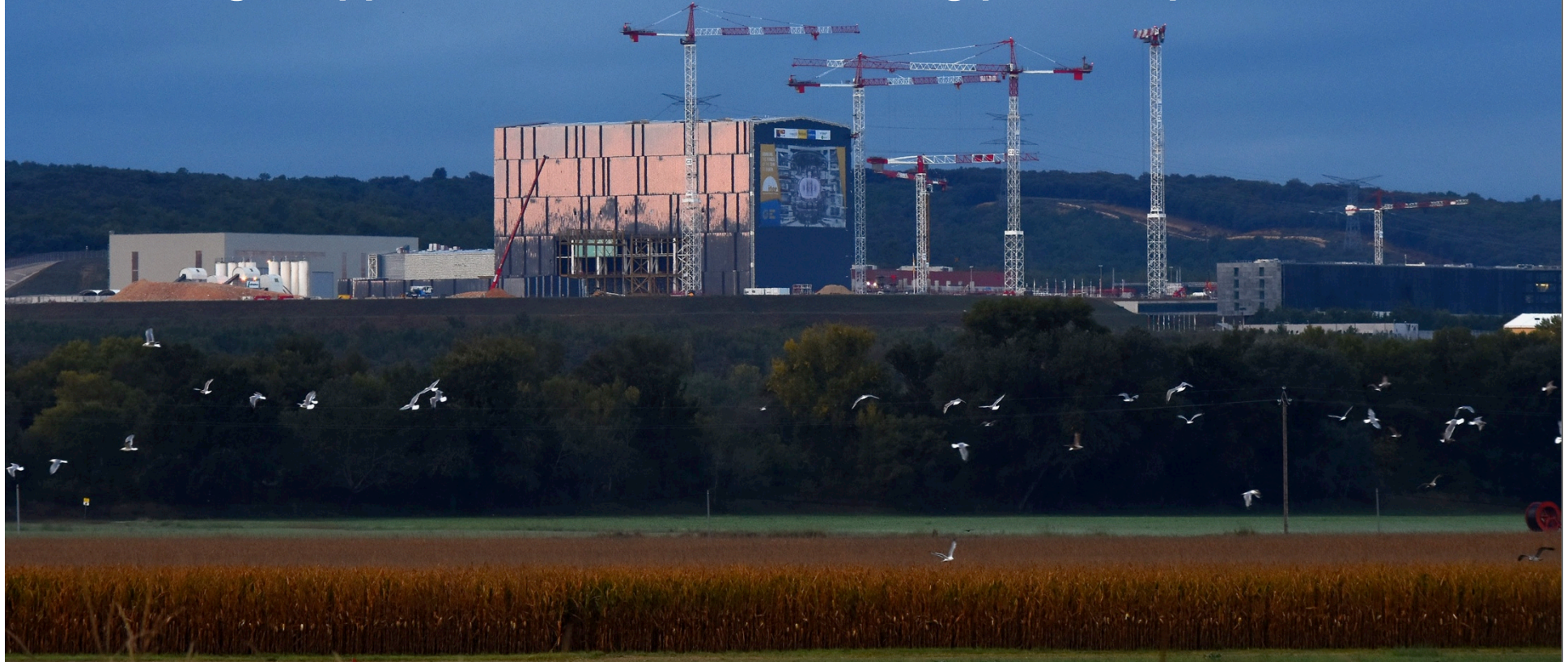
France

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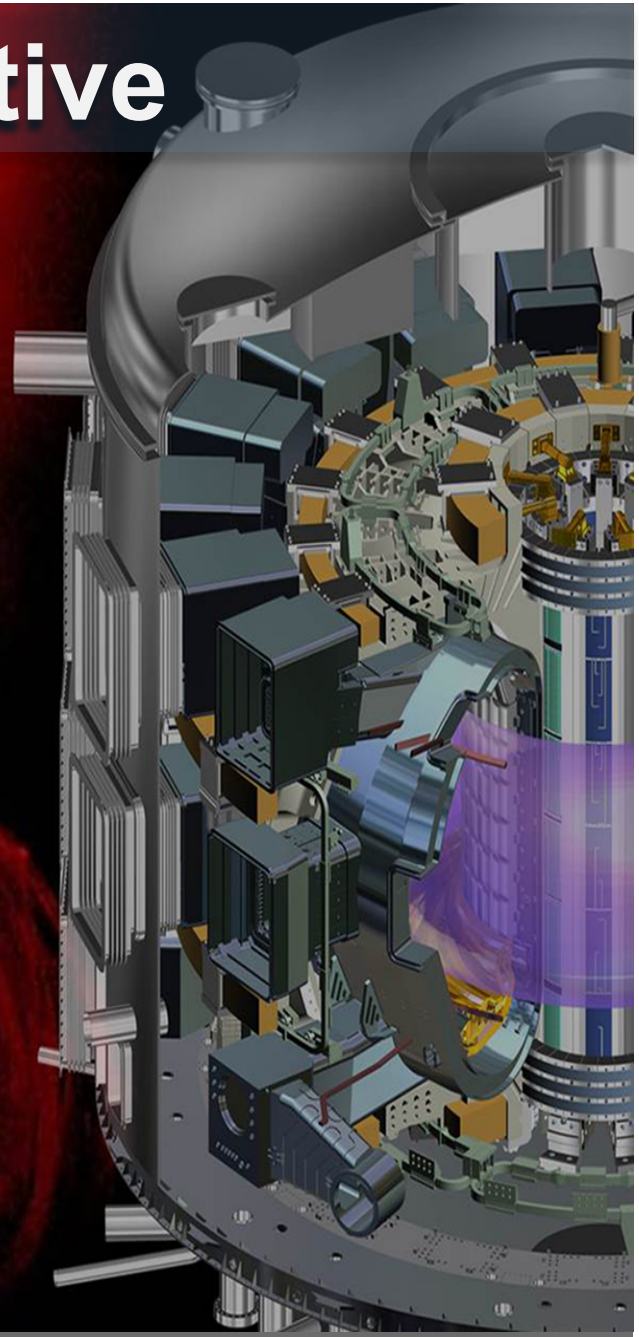
Synopsis

- Development of the revised ITER baseline schedule
- Current status of project R&D, manufacturing and construction
- Staged approach towards ITER burning plasma operation



ITER in perspective

- **ITER Program Objective:**
 - to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes
- **Key Technical Goals:**
 - achieve extended burn of a DT plasma with dominant alpha-particle heating ($Q \geq 10$, ~ 500 s)
 - develop steady-state fusion power production as ultimate goal
 - integrate and test all essential fusion power reactor technologies and components
 - demonstrate safety and environmental acceptability of fusion



Revised ITER Baseline Schedule

2015: the Action Plan



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
- ✓ Developed and promoted a strong, organization-wide nuclear project culture
- ✓ Conducted comprehensive integrated bottom-up review of all activities, systems, structures, and components to build the ITER machine
 - ✓ Identified need for a revised resource-loaded schedule for timely, cost-effective construction and operation through start of D-T plasma.

Baseline Schedule Development

IO-CT and IO-DAs worked intensively on the development of a revised resource-loaded baseline schedule throughout 2015

- ✓ In September 2015, IO-CT and IO-DAs held Integrated Review Meeting to review proposed schedule and IO-CT resource estimates
- ✓ In November 2015, project management proposed to ITER Council:
 - ✓ 'Best technically achievable' schedule
 - ✓ First Plasma in December 2025 and DT Operation in late 2032
- ✓ Council accepted proposal as a basis for managing project over subsequent 2 years:
 - ✓ Based on project's proposal for achievement of major milestones
- ✓ Requested independent review of schedule to establish viability
 - ✓ Appointed 'Independent Council Review Group' of experts nominated by Members to assess reliability and credibility of schedule
 - ✓ review IO resources required to achieve First Plasma milestone

April 2016: intensive, in-depth review by independent expert group declares:



- “...substantial improvement in project performance...”
- “...high degree of motivation...”
- “...considerable progress during the past 12 months...”
- “...sequence and duration of future activities have been fully and logically mapped in the resource-loaded schedule...”
- “...resource estimate is generally complete [...] and provides a credible estimate of cost and human resources...”

2016: Performance & Follow-through

Code	Name	ORG 1	Target	
01	Tier-1 of Cryostat base Section deliver to IN-DA Workshop at ITER Site	IN	Q1 2016	●
02	Start of B1 Civil works in Tokamak Building	EU	Q1 2016	●
03	Lot-1 Piping - Delivered by IN-DA to IO at ITER-Site	IN	Q1 2016	●
04	Erection of Tokamak Main Cranes in Assembly Hall	EU	Q2 2016	●
05	Completion of First EU TF Winding Pack	EU	Q2 2016	●
06	Fabrication of all TF Conductors from RF, CN and JA Completed	CN,JA,RF	Q2 2016	●
07	All Magnet Conductor Fabrication Complete for PF5 and PF2	CN	Q2 2016	●
08	Completion of Performance Tests of Full-W Divertor OVT Plasma Facing Units	JA	Q2 2016	●
09	Installation of WDS Tanks in Tritium Building	EU	Q2 2016	●
10	Complete CS Module 1 Winding	US	Q2 2016	●
11	Signature of CMA Contract	IO	Q3 2016	●
12	Complete 4th (of 9) TF Conductor Unit Length	US	Q3 2016	●
13	First Sub Segment Assembly VV Sector 5 Completed	EU	Q4 2016	●
14	First Liquid Nitrogen Refrigerator Equipment Factory Acceptance Tests Completed	EU	Q4 2016	●
15	Steady State Electrical Network - Delivery of Power Transformers (Lot 3) to ITER	US	Q4 2016	●
16	Liquid Helium plant equipment Factory Acceptance Test Completed	IO	Q4 2016	●
17	Vacuum		2016	●
18	Comple		2017	●
19	Energis		2017	●
20	Start of		2017	●

From July 2016 Progress Report

Blue – completed

Green - on schedule

Yellow – delays anticipated

Red – delayed, mitigation needed

Schedule Control

- ✓ Main issue at present relates to Vacuum Vessel delivery
 - ✓ Transfer of 2 VV sectors from EU to IO (manufactured in KO)
 - ✓ Reconfigure VV Assembly sequence to maintain FP schedule
- ✓ Technical measures to support schedule/ reduce risk
 - ✓ Accelerate interface freeze
 - ✓ VVPSS redesign
 - ✓ Establish Nuclear Integration Unit to coordinate nuclear analysis
 - ✓ Finalize Tokamak Complex Floor Response Spectra

Strong performance: meeting demands of external validation while maintaining construction and manufacturing at full pace in accordance with agreed milestones

18th ITER Council (June 2016) endorses updated schedule



The 18th ITER Council, chaired by Korea's Won Namkung, convened at ITER Headquarters in Saint-Paul-lez-Durance on 15-16 June 2016.

First Plasma in December 2025

The updated Schedule is challenging but technically achievable.

It represents the best technically achievable path forward to First Plasma.

The successful completion of all project milestones to date, on or ahead of schedule, is a positive indicator of the collective capacity of the ITER Organization and the Domestic Agencies to continue to deliver on the updated Schedule.

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

Baseline Schedule: Staged Approach

Developed in parallel with ICRG assessment to incorporate resource constraints of Members

- ✓ 4-stage approach foresees several phases of operation from FP to DT
 - ✓ Staged upgrades of ITER facility following FP in December 2025
 - ✓ First DT operations phase scheduled for December 2035
- ✓ ICRG recommended to Extraordinary Council in April 2016 that Staged Approach provides most appropriate framework for revised schedule development
- ✓ ITER Council in June 2016 approved *ad referendum* schedule to First Plasma in December 2025
- ✓ Council requested Director-General to develop revised overall schedule and IO-CT resource estimate to DT Commissioning within framework of Staged Approach
 - ✓ Updated Baseline schedule and IO-CT resource estimate to FP
 - ✓ Indicative schedule and cost baseline from 2026 to initial DT operations

Staged Approach: Configuration Workshop

Configuration Workshop held by IO-CT and IO-DAs in June 2016 to define Plant Configuration for each Operations phase

- ✓ Plant Configuration for each Operations Phase agreed on basis of industrial experience and Members' budget constraints
- ✓ 7 outstanding configuration issues identified and resolved

Staged Approach: Research Plan Workshop

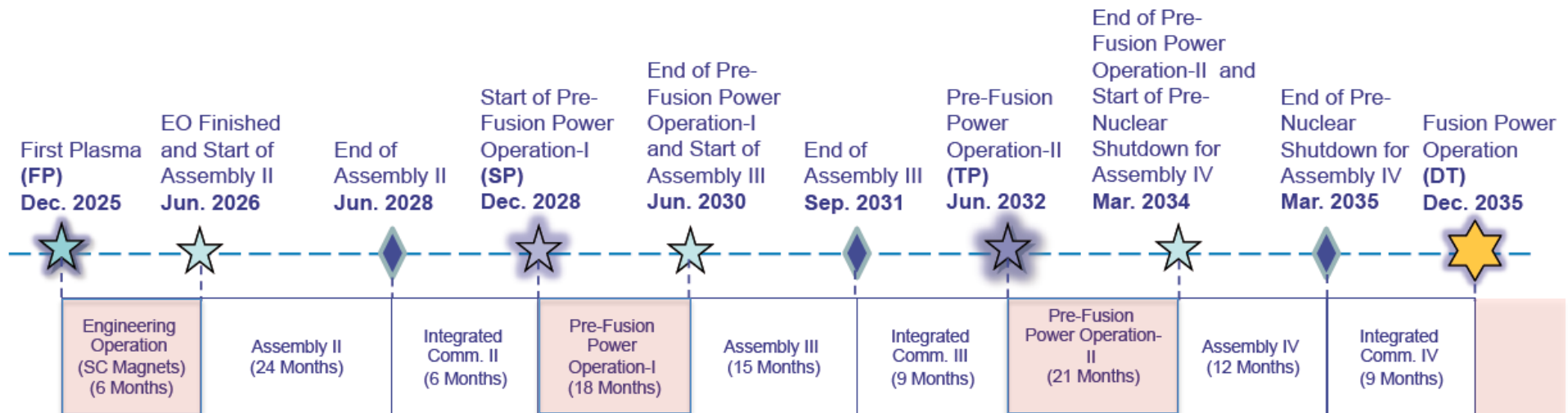
Research Plan Workshop held by IO-CT, and Members' fusion experts in July 2016 to define experimental programme from First Plasma to initial DT operation

- ✓ Experimental programme developed around agreed evolution of Plant Configuration
 - ✓ Key experimental goals for each phase of Operations agreed
 - ✓ Principal experimental risks and physics issues identified ⇒ further R&D

Staged Approach: Baseline Schedule

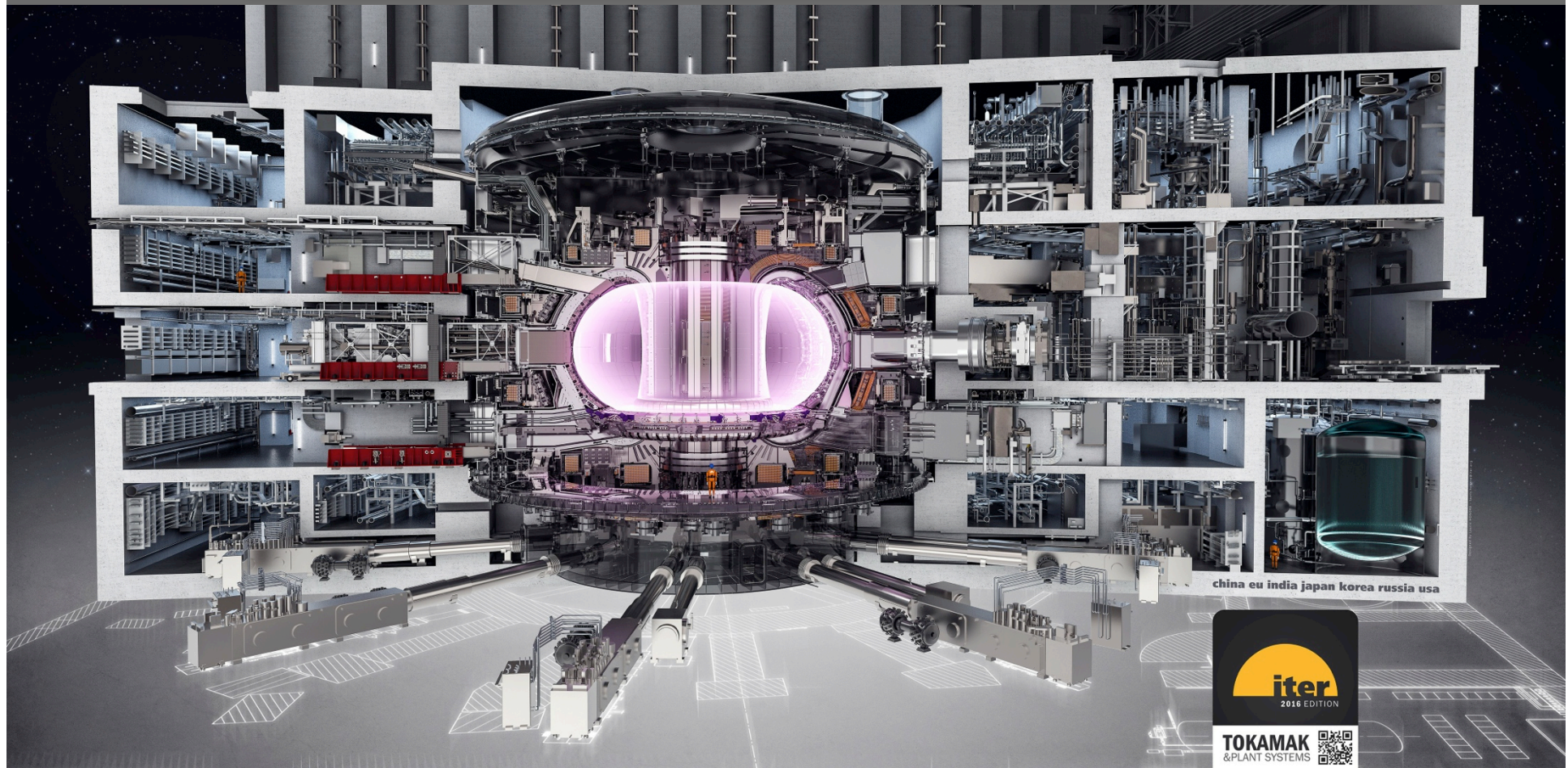
Extensive interactions among IO-CT and IO-DAs to resolve outstanding issues to finalize revised baseline schedule proposal

- ✓ Schedule and IO-CT resource estimate to First Plasma consistent with Members' budget constraints
- ✓ Director-General proposes resolution of 4-stage/3-stage approach in favor of 4-stage: consistent with Members' financial and technical constraints



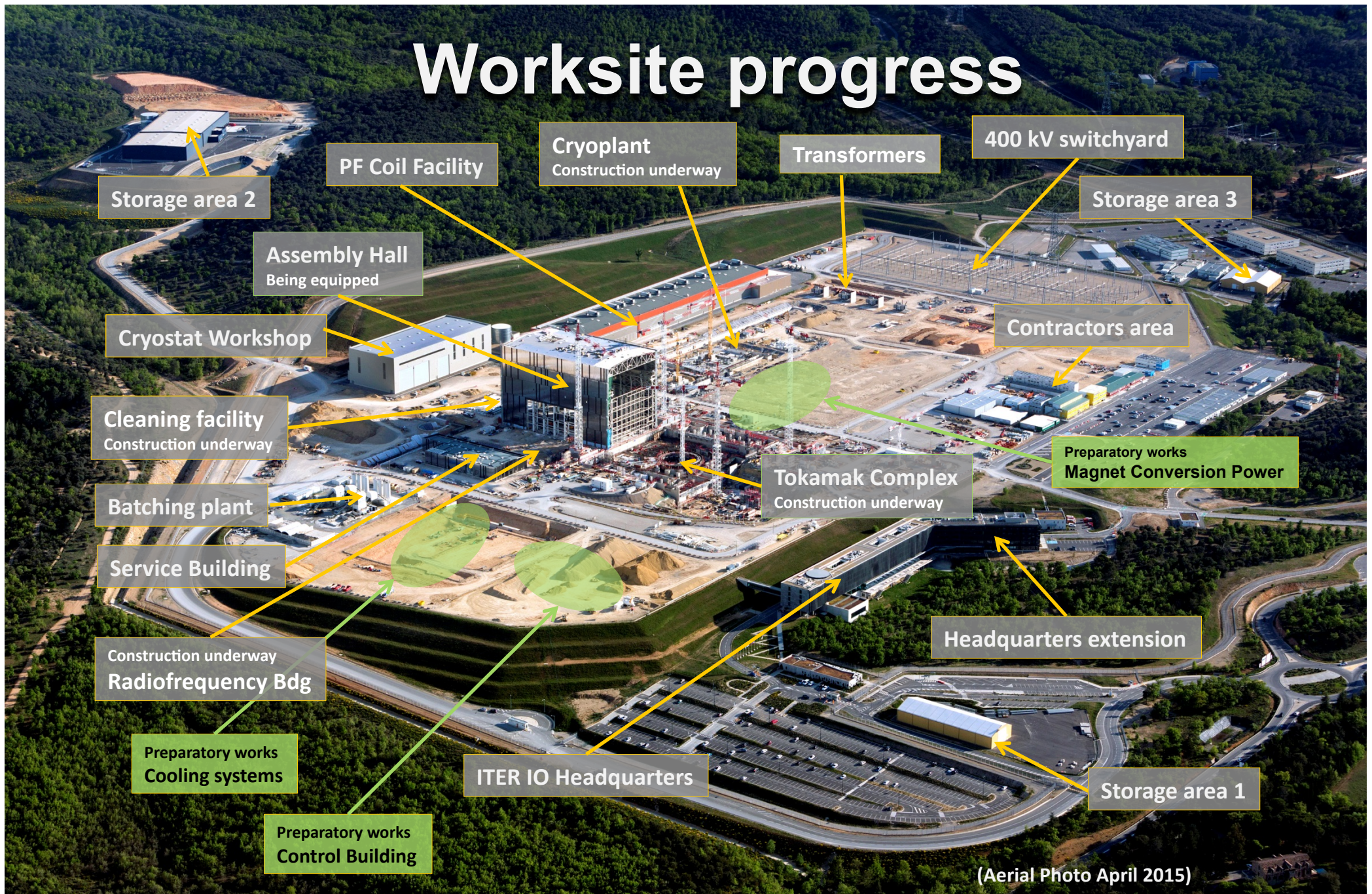
Current Project Status

Tokamak Building



A north-south cutaway of the Tokamak Building, which is the major element of the Tokamak Complex, together with the Diagnostics Building and the Tritium Building

Worksite progress

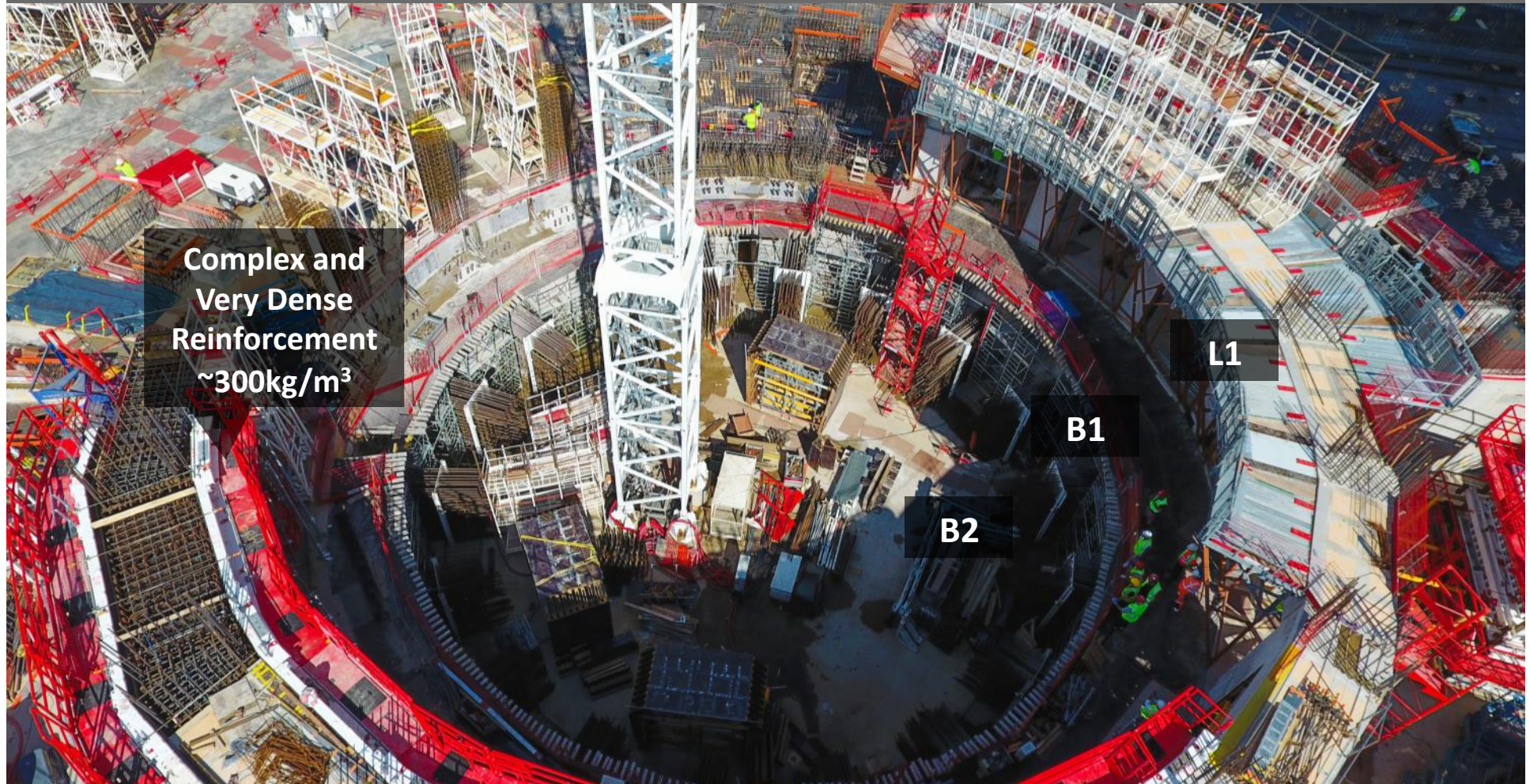


Tokamak Complex



Resting on 493 seismic pads, the reinforced concrete “B2” slab bears the 400 000-ton Tokamak Complex. Concrete casting of the B2 slab was finalized on August 27, 2014. Diagnostic Building (right): B1 level slab and walls/columns now complete; Tokamak Building (centre): completion of the BioShield wall B2 level. Start of the B1 slab on 26 April 2016, and construction of interior walls/columns is on-going. Tritium Building (left): steel reinforcement on B1 level.

Tokamak Complex



Close-up of Tokamak Complex Bioshield

Tokamak Complex

First plant components installed (detritiation tanks)

The six water detritiation tanks (four 20 m³ tanks and two 100 m³ tanks) and the drainage tank are the first plant components installed in the ITER Tokamak Complex.

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Assembly Hall



Before being integrated in the machine, the components will be prepared and pre-assembled in this 6,000 m², 60-metre high building. The Assembly Hall is equipped with a double overhead travelling crane with a total lifting capacity of 1,500 tons.

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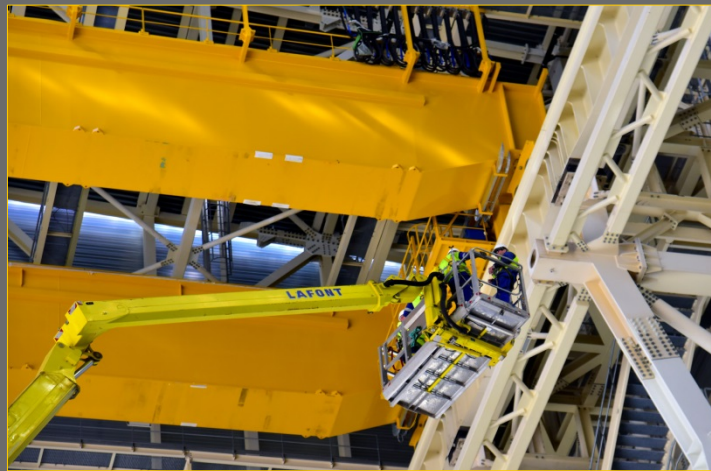
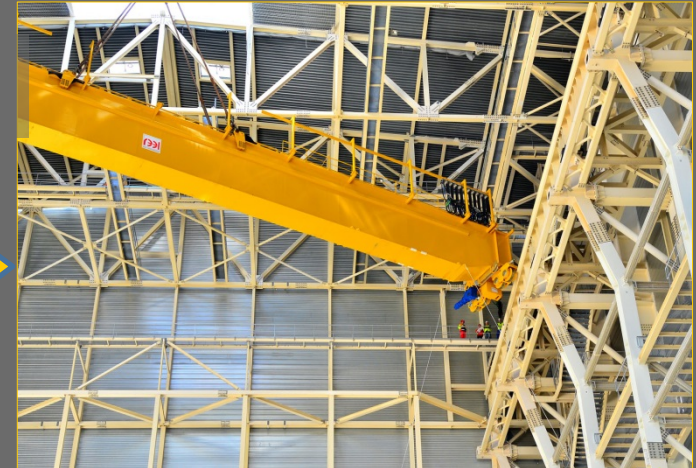
Assembly Hall

43 metres above the building's basemat
the double overhead crane is now installed



▶ On 14 June lifting operations begin.

Complete with gear-motors, wheels, braces, electrical gear, etc. , the beam now weighs 186 tons.



▶ Each pair of cranes will have a lifting capacity of 750 tons.

On 22 June, the 4 beams and 2 of 4 trolleys (100 t.) are installed.



Radiofrequency heating

Adjacent to the Assembly Hall , the building that will house the plasma heating systems (microwave and radio frequency) is being built .

Cryostat Workshop

The welding operations of the cryostat base (1250 tonne) started 8 September 2016.

Cryoplant



It will be the largest single-platform cryoplant in the world. The ITER Cryoplant will distribute liquid helium (~ 4.2 K) and liquid nitrogen (77 K) to various machine components (superconducting magnets, thermal shield, cryopumps, etc.).

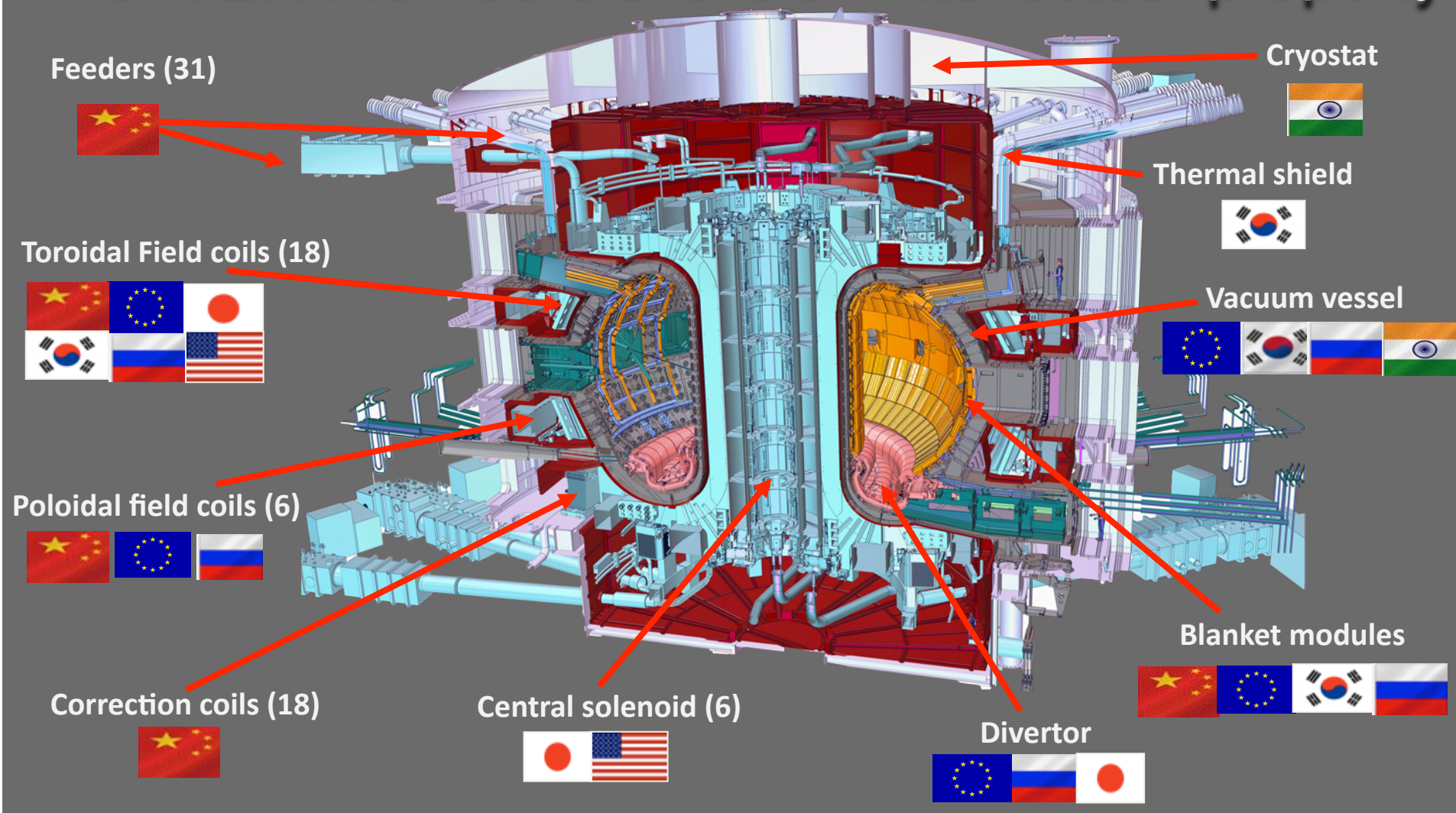
PF Coil winding facility



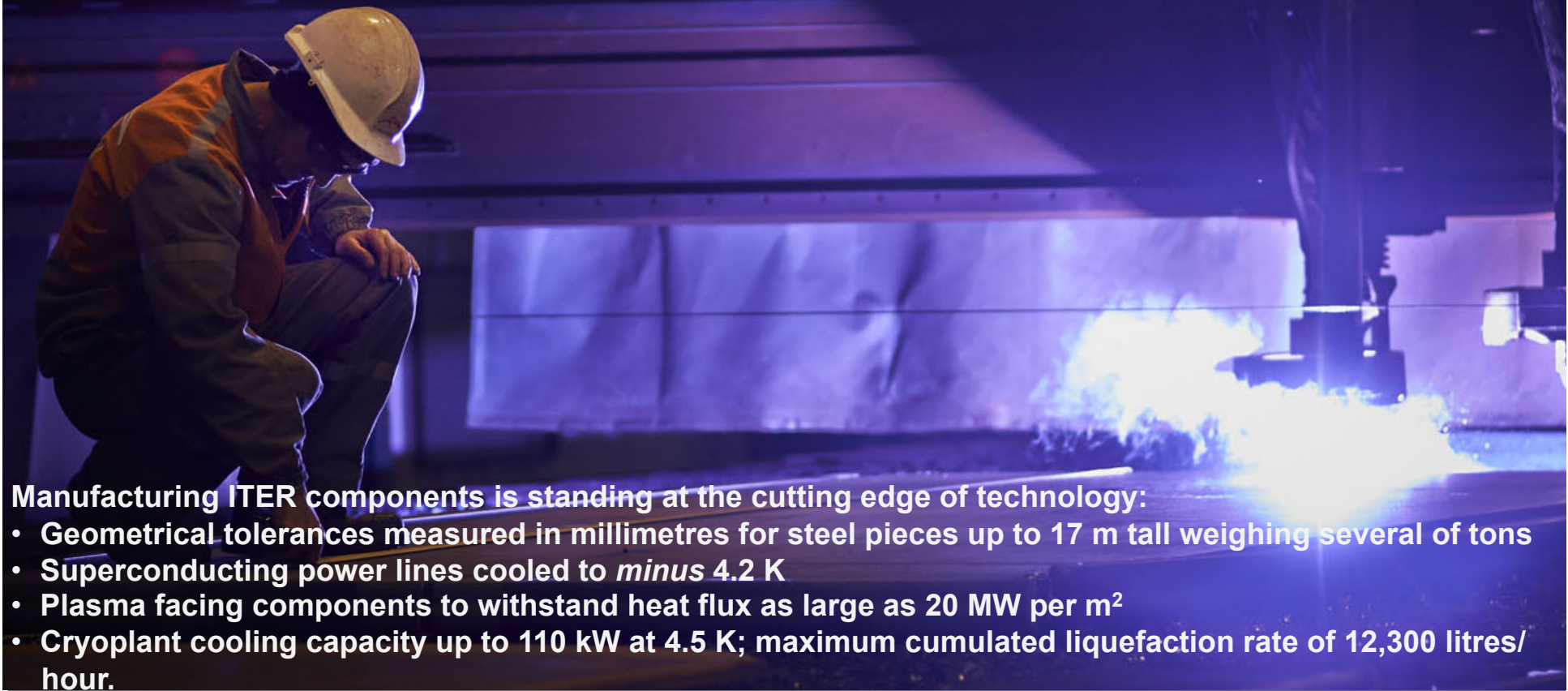
Too large to be transported by road, four of ITER's six ring-shaped magnets (the poloidal field coils, 8 to 24 m in diameter) will be assembled by Europe in this 12,000 m² facility. Winding table is now commissioned, manufacturing operations (mockup) began in July.

Who manufactures what?

The ITER Members share all intellectual property



Entering the industrial phase with highly challenging specifications



Manufacturing ITER components is standing at the cutting edge of technology:

- Geometrical tolerances measured in millimetres for steel pieces up to 17 m tall weighing several of tons
- Superconducting power lines cooled to *minus* 4.2 K
- Plasma facing components to withstand heat flux as large as 20 MW per m²
- Cryoplant cooling capacity up to 110 kW at 4.5 K; maximum cumulated liquefaction rate of 12,300 litres/hour.

Manufacturing progress



China



Internal components of an in-cryostat feeder prototype.



Correction coil at ASIPP in Hefei, China.

Magnet Systems, Power Systems, Blanket, Fuel Cycle, Diagnostics

Manufacturing progress



China



Tooling for Poloidal Field coil #6 (the second-smallest ring-shaped ITER magnet, at 350 tons, 10 m in diameter), is complete and is being commissioned at ASIPP in Hefei, China.



The first of three power transformers for the pulsed electrical network. Delivery is underway.

Magnet Systems, Power Systems, Blanket, Fuel Cycle, Diagnostics

Manufacturing progress



EU



The first toroidal field coil winding pack – the 110-ton inner core of ITER's D-shaped superconducting TF Coils – was completed in April.



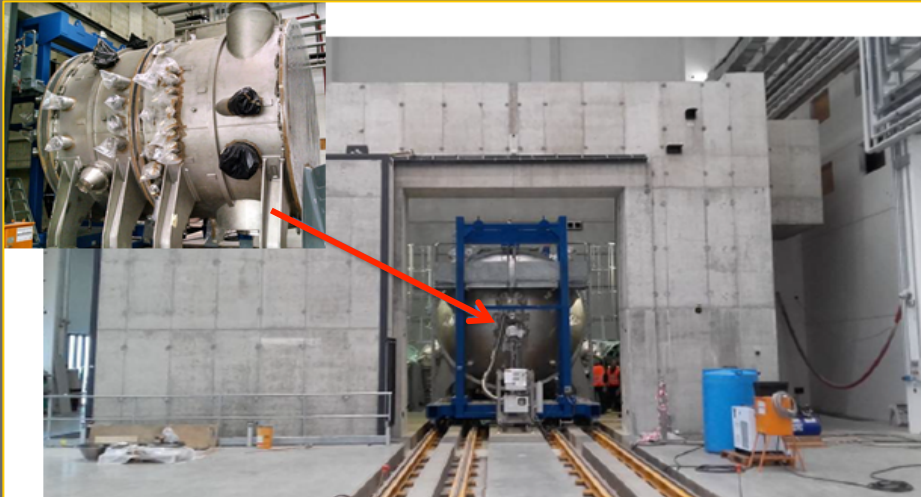
Inspection of the liquid helium tank inner vessel for the ITER cryoplat.

Buildings, Magnet Systems, Heating & Current Drive Systems, Vacuum Vessel, Divertor, Blanket, Power Systems, Fuel Cycle, Tritium Plant, Cryoplat, Diagnostics, Radioactive Materials

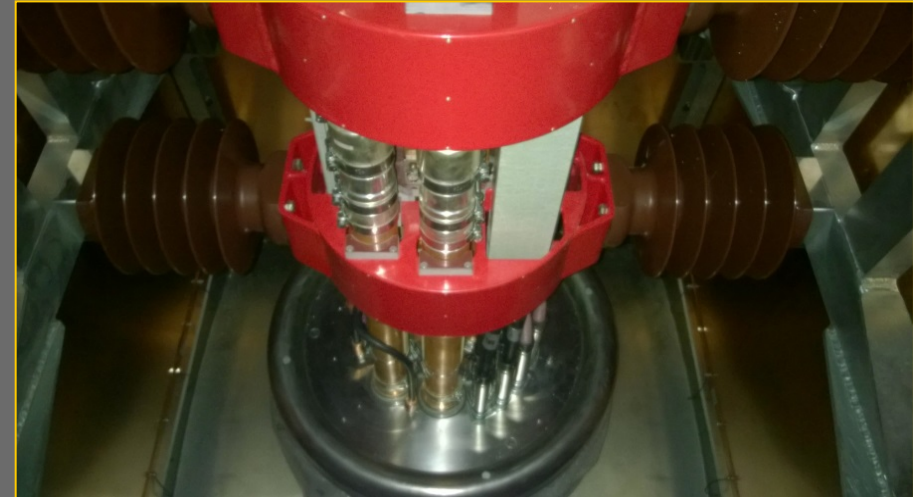
Manufacturing progress



EU



SPIDER vacuum vessel installed inside bio-shield at the PRIMA Neutral Beam Test facility in Padova, Italy.



SPIDER TL connected to vacuum vessel electrical bushing.

Buildings, Magnet Systems, Heating & Current Drive Systems, Vacuum Vessel, Divertor, Blanket, Power Systems, Fuel Cycle, Tritium Plant, Cryoplant, Diagnostics, Radioactive Materials

Manufacturing progress



India



India is responsible for fabrication and assembly of the 30x30 meter ITER cryostat. The base plates were delivered to ITER in December 2015.



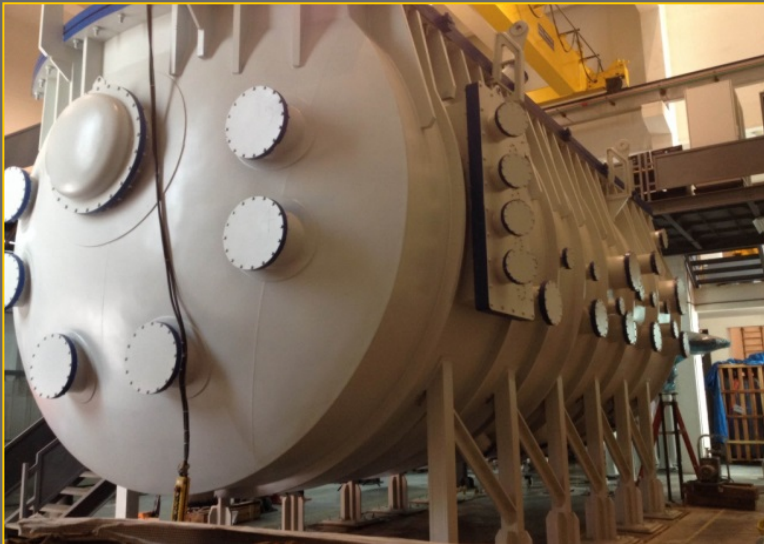
The transportation frame/assembly and welding support for the cryostat has been assembled in the Cryostat Workshop where welding began in August.

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

Manufacturing progress



India



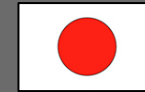
Diagnostic neutral beam vacuum vessel.



A cold test was successfully completed on a prototype cryoline.

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

Manufacturing progress



Japan



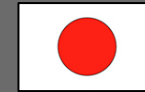
Connection of segments for the first inboard Toroidal Field Coil structure (completed in November 2015), a significant achievement for TF coil procurement.



Toroidal field coil heat treatment.

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

Manufacturing progress



Japan



Series production of central solenoid conductor continues. 19 conductors have already been delivered to the US.



In October 2015, the first batch of components for the neutral beam test facility were shipped to the PRIMA facility in Italy.

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

Manufacturing progress



Korea



At Hyundai Heavy Industries, where 2 of 9 vacuum vessel sectors are under construction, welding on the upper section of the inner shell for Sector #6.



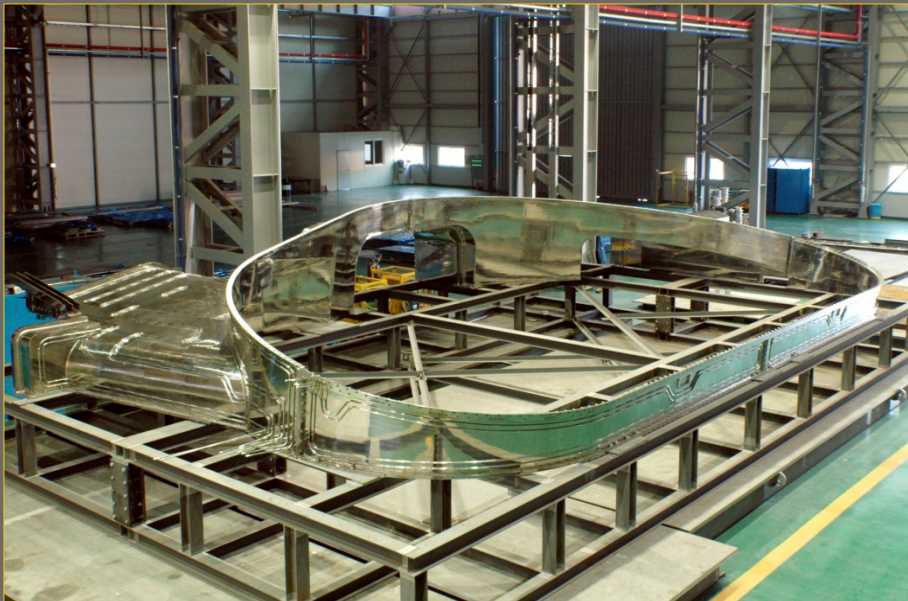
Inner shell assembly of a lower port stub extension for the vacuum vessel.

Vacuum Vessel, Blanket, Power Systems, Magnet Systems, Thermal Shield,
Assembly Tooling, Tritium Plant, Diagnostics

Manufacturing progress



Korea



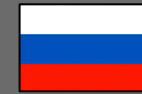
At Sam Hong Machinery in Changwon, fabrication is progressing on all nine 40° thermal shield sectors.



Welding has begun on parts of the first 800-ton Sector Sub-Assembly Tool. Korea is designing and manufacturing 128 purpose-built tools for assembly.

Vacuum Vessel, Blanket, Power Systems, Magnet Systems, Thermal Shield, Assembly Tooling, Tritium Plant, Diagnostics

Manufacturing progress



Russia



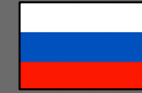
Russia completes its share of toroidal field conductor in June 2015, marking the end of a 5-year campaign to manufacture 28 production lengths (more than 120 tons of material).



In December 2014, specialists at the Efremov Institute successfully tested a prototype of the fast discharge resistor module, designed to rapidly discharge energy stored in the coils of the ITER magnetic system. Tests results demonstrated full conformance with ITER Organization technical requirements.

Power Systems, Magnet Systems, Blanket, Divertor, Vacuum Vessel, Diagnostics, Heating & Current Drive Systems

Manufacturing progress



Russia



Fabrication and qualification tests of PF1 winding pack stack sample were successfully completed.



Winding of first double pancake for poloidal field coil #1 inside the clean room.

Power Systems, Magnet Systems, Blanket, Divertor, Vacuum Vessel, Diagnostics, Heating & Current Drive Systems

Manufacturing progress



USA



General Atomics is fabricating the 1000-ton Central Solenoid (CS). In April 2016, winding of the first CS module was completed.



Module tooling stations are in place and being commissioned, including the heat treatment furnace shown here.

Cooling Water System, Magnet Systems, Diagnostics, Heating & Current Drive Systems, Fuel Cycle, Tritium Plant, Power Systems

Manufacturing progress



USA



Steady state electrical network transformers have been delivered to the ITER site.



US will complete toroidal field coil production in 2017.

Cooling Water System, Magnet Systems, Diagnostics, Heating & Current Drive Systems, Fuel Cycle, Tritium Plant, Power Systems

The deliveries succeed one another...



... to provide door-to-door delivery



14 January 2015:	First of four 90-ton transformers procured by the US and manufactured in Korea
20 March 2015:	Detritiation tank (20 tons), procured by Europe
2 April 2015:	Detritiation tank (20 tons), procured by Europe
20 April 2015:	Second of four 90-ton transformers procured by the US and manufactured in Korea
7 May 2015 :	Two 80-ton, 61,000-gallon drain tanks for the tokamak cooling water system, procured by US
21 May 2015:	Three 90-ton transformers procured by the US and manufactured in Korea
17 Sept 2015:	Two drain tanks (79 t.) for the cooling system, one (46 t.) for the neutral beam system
10 & 17 Dec. 2015:	Six 60° segments for tier 1 of the cryostat base by India (<i>photo</i>)
18 & 25 March 2016:	Girder # 1 & 2 (out of 4) for the Assembly Hall gantry crane (Europe)
21 April 2016:	Girder # 3 & 4 for the Assembly Hall gantry crane (Europe) – <i>pictured</i>
10 June 2016	First of three 300-ton PPEN transformer (China)

CMA contract for assembly and installation



In June, ITER Organization signed a 10-year €174 million contract with the MOMENTUM joint venture, to manage and coordinate the assembly and installation of the Tokamak and associated plant systems.

MOMENTUM

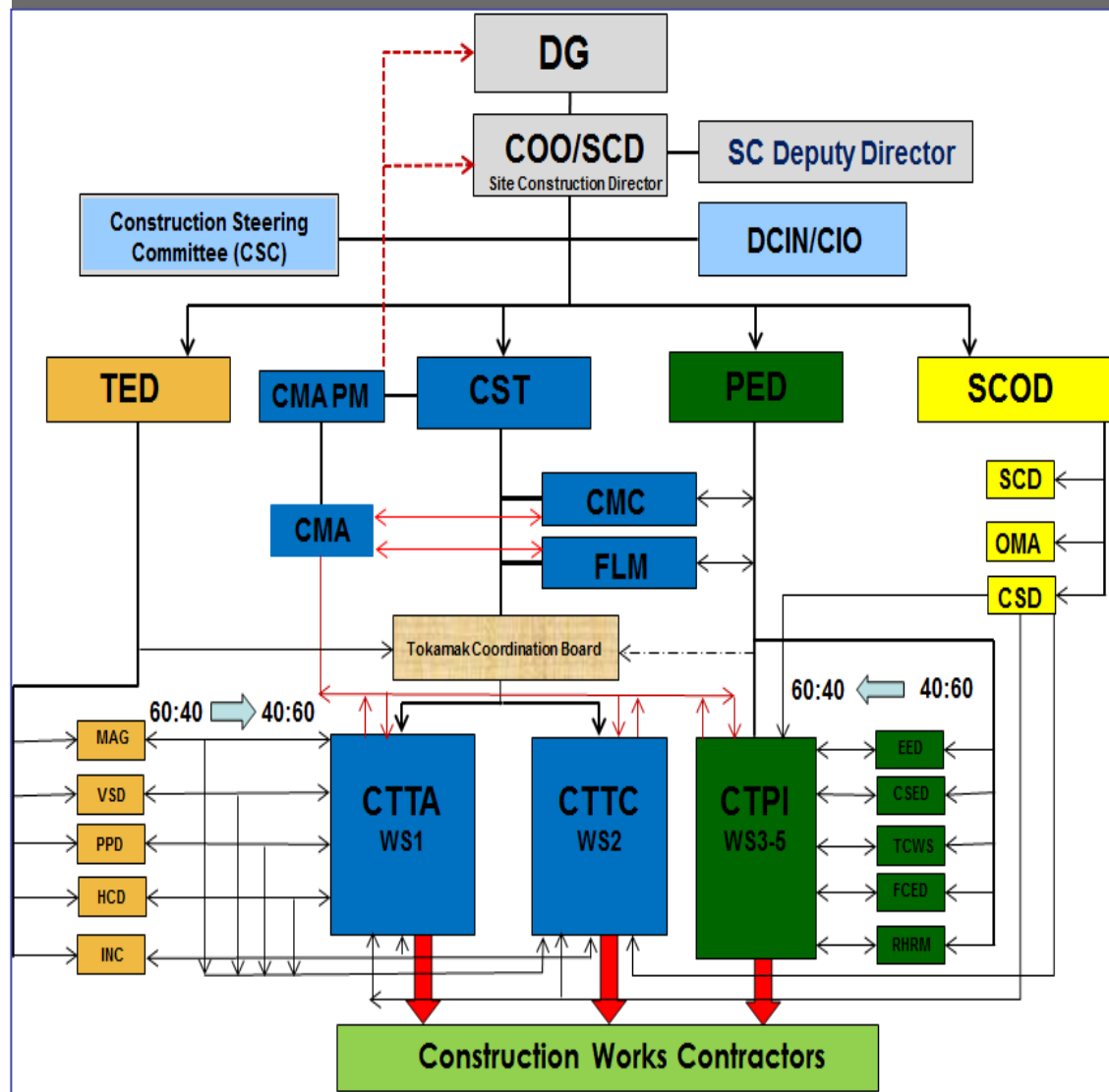


amec
foster
wheeler

assystem



Construction Organization



□ In order to accelerate and focus more on construction activities, IO made a transformation to “Construction Organization (Phase 1)”, focusing on three main areas (TA, TC, PI):

□ Main works contracts for three areas (Electrical, Mechanical and Tokamak) preparation well advanced.

Engineering innovation: superconductors

200 km, 2,800 tons of superconductors (80% of the total required) have been manufactured and validated

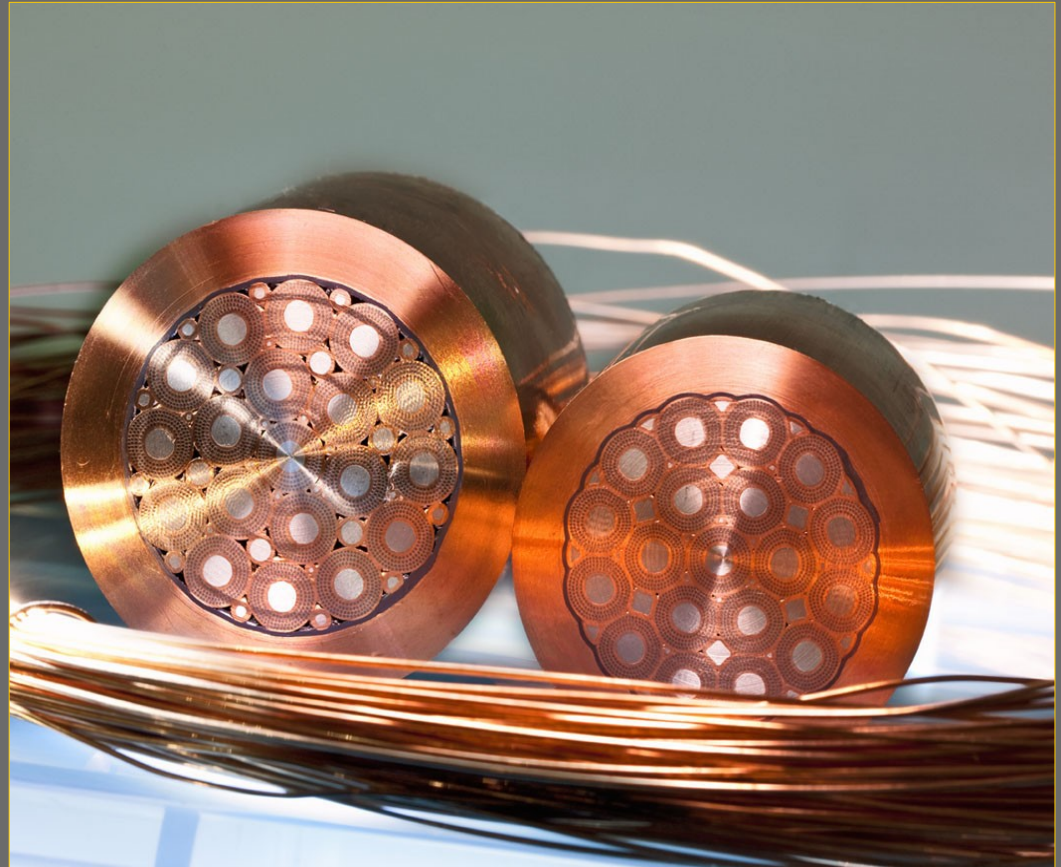
Six ITER Members—China, Europe, Japan, Korea, Russia and the United States—have been responsible for the production of cable-in-conduit conductors worth a total of EUR 610 million.

The eight-year campaign to produce the superconductors for ITER's powerful magnet systems is in its final stages.

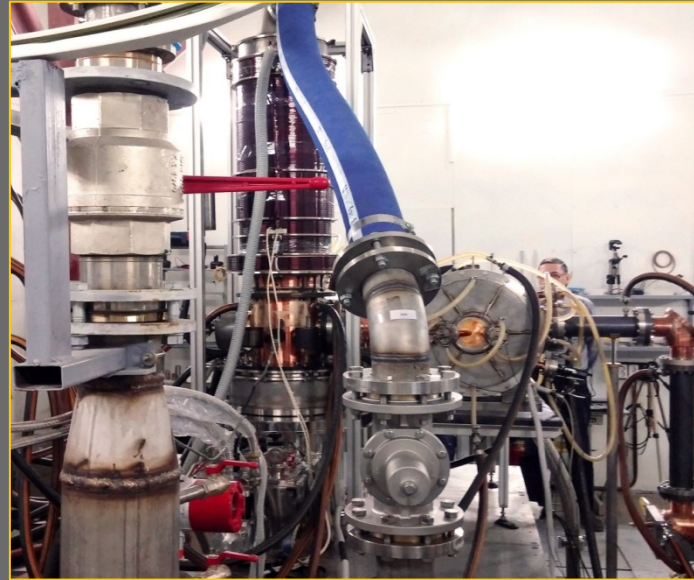
***Harmonized global standards for production methods, quality controls, testing protocols, etc.**

***Groundbreaking work in materials science.**

***Largest superconductor procurement in industrial history.**



Engineering innovation: gyrotrons



Gyrotron prototype developed by RF-DA.

Gyrotron prototype developed by F4E (EU-DA).

Gyrotron prototype developed by JA-DA.



Engineering innovation: pellet fueling and ELM (edge localized mode) pacing



Dual nozzle prototype developed at ORNL (Oak Ridge National Laboratories, USA).

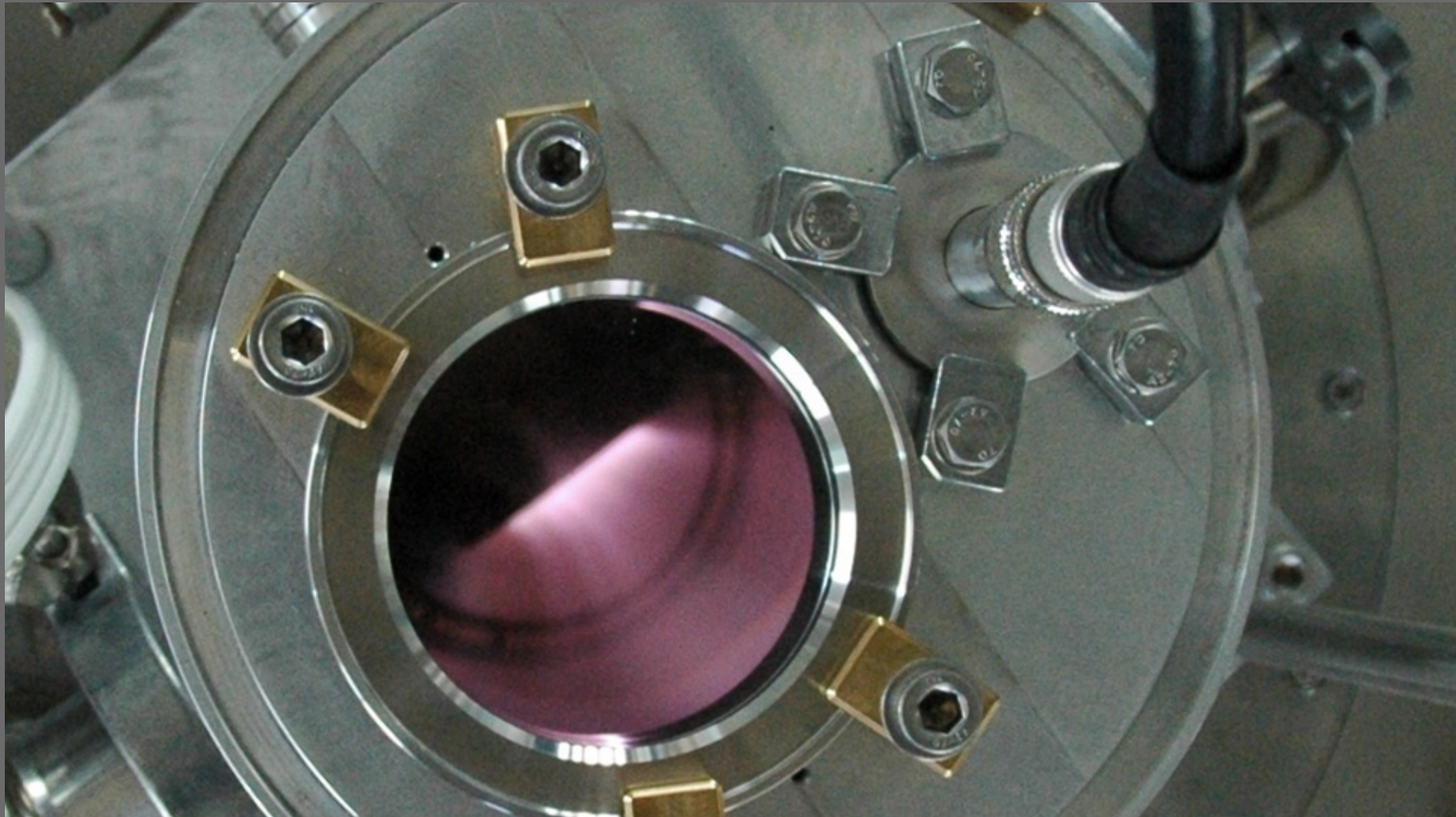


Twin screw pellet extruder developed at ORNL.



View of the drive shaft gears and top of the twin-screw extruder mechanism.

Engineering innovation: cleaning methods



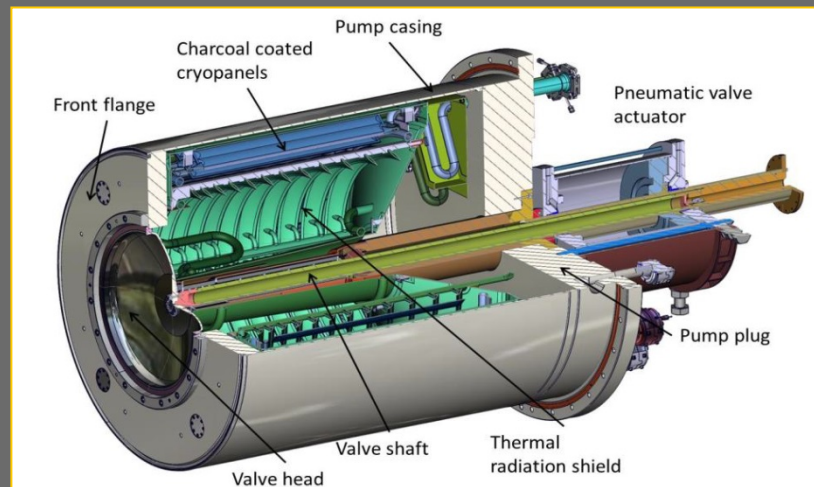
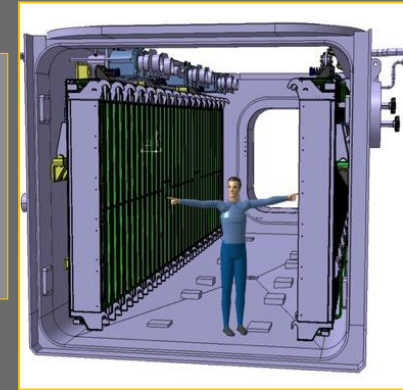
New cleaning techniques are being developed for ITER first mirrors.

Engineering innovation: vacuum systems



8-tonne machined flange of the first Torus Cryo-pump

Neutral Beam Injection Cryo-pump: 8 meters long, 2.8 meters high



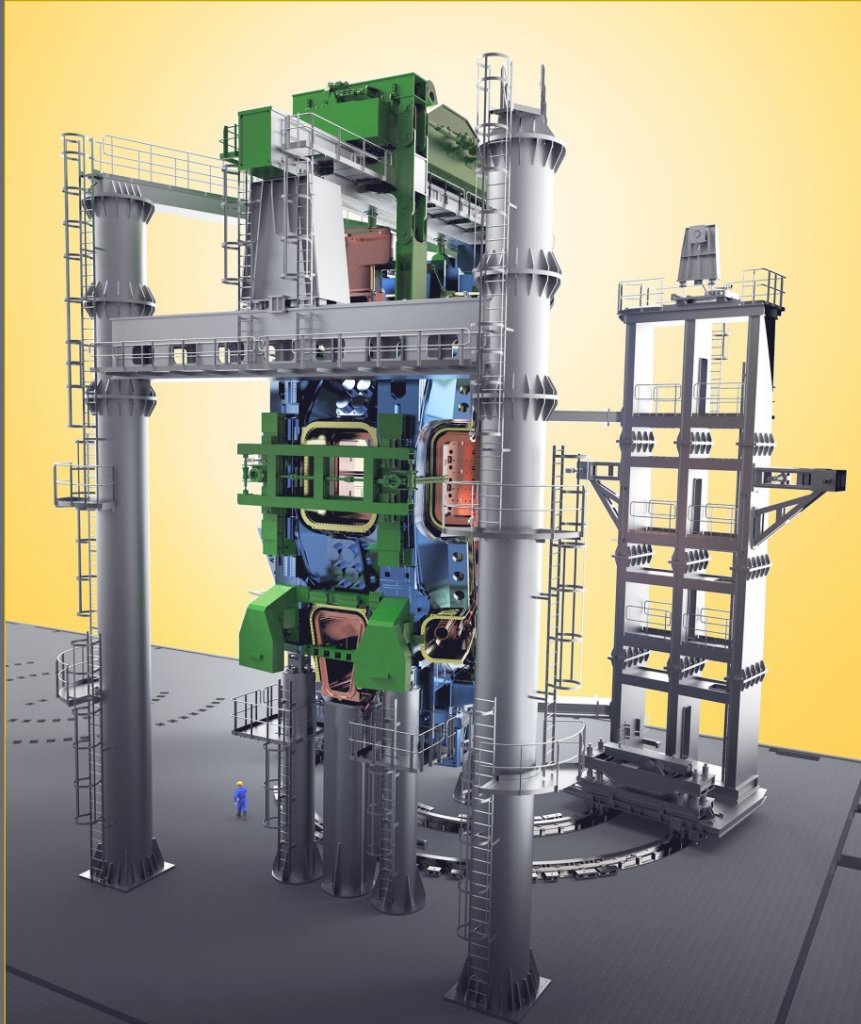
Torus and Cryostat Cryo-pump (1.8 meter diameter)

The ITER vacuum system will be one of the largest, most complex vacuum systems ever built: the cryostat, at $\sim 8500\text{m}^3$; the torus, at $\sim 1330\text{m}^3$; the neutral beam injectors at $\sim 180\text{m}^3$ each; plus lower volume systems.

More than 400 vacuum pumps will employ 10 different technologies.

Final design involved new fabrication methods to reduce cost and manufacturing time of cryo-panels and thermal shields within the pumps.

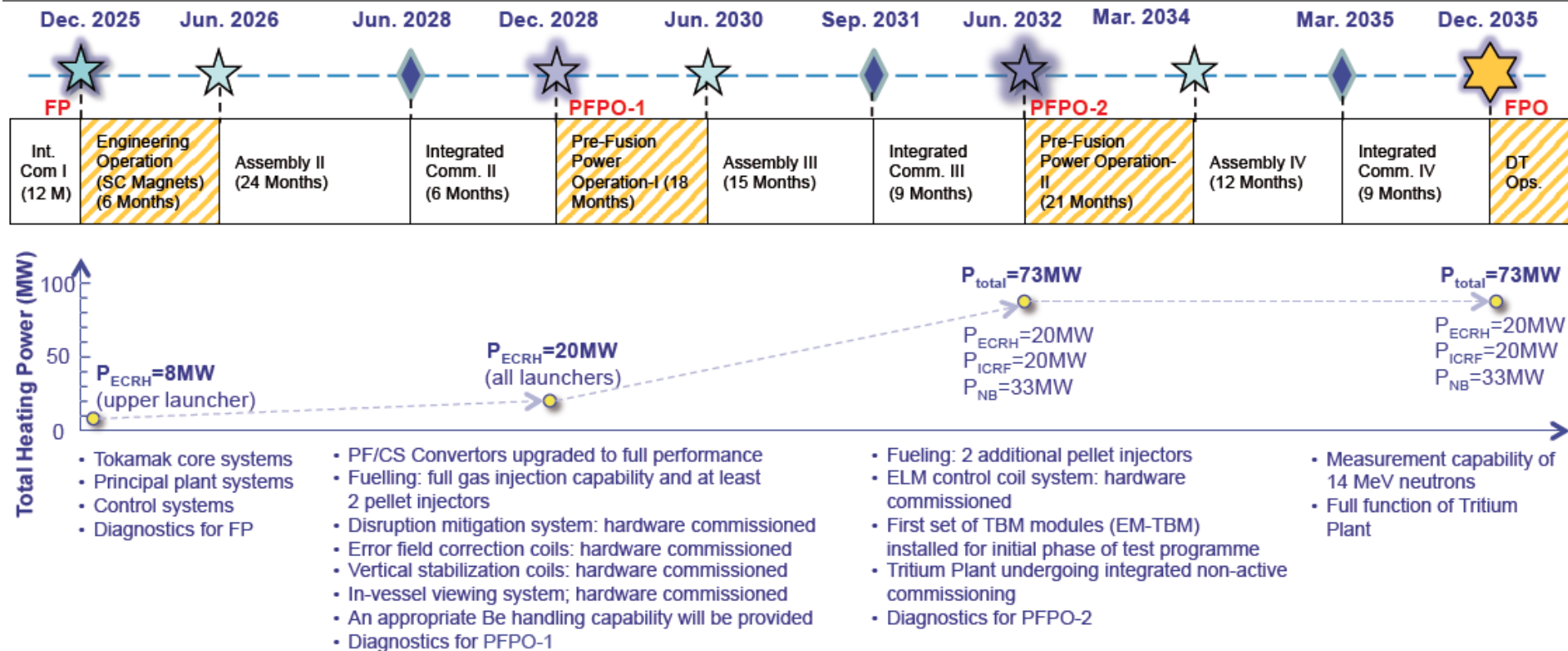
Engineering innovation: robotics and remote handling



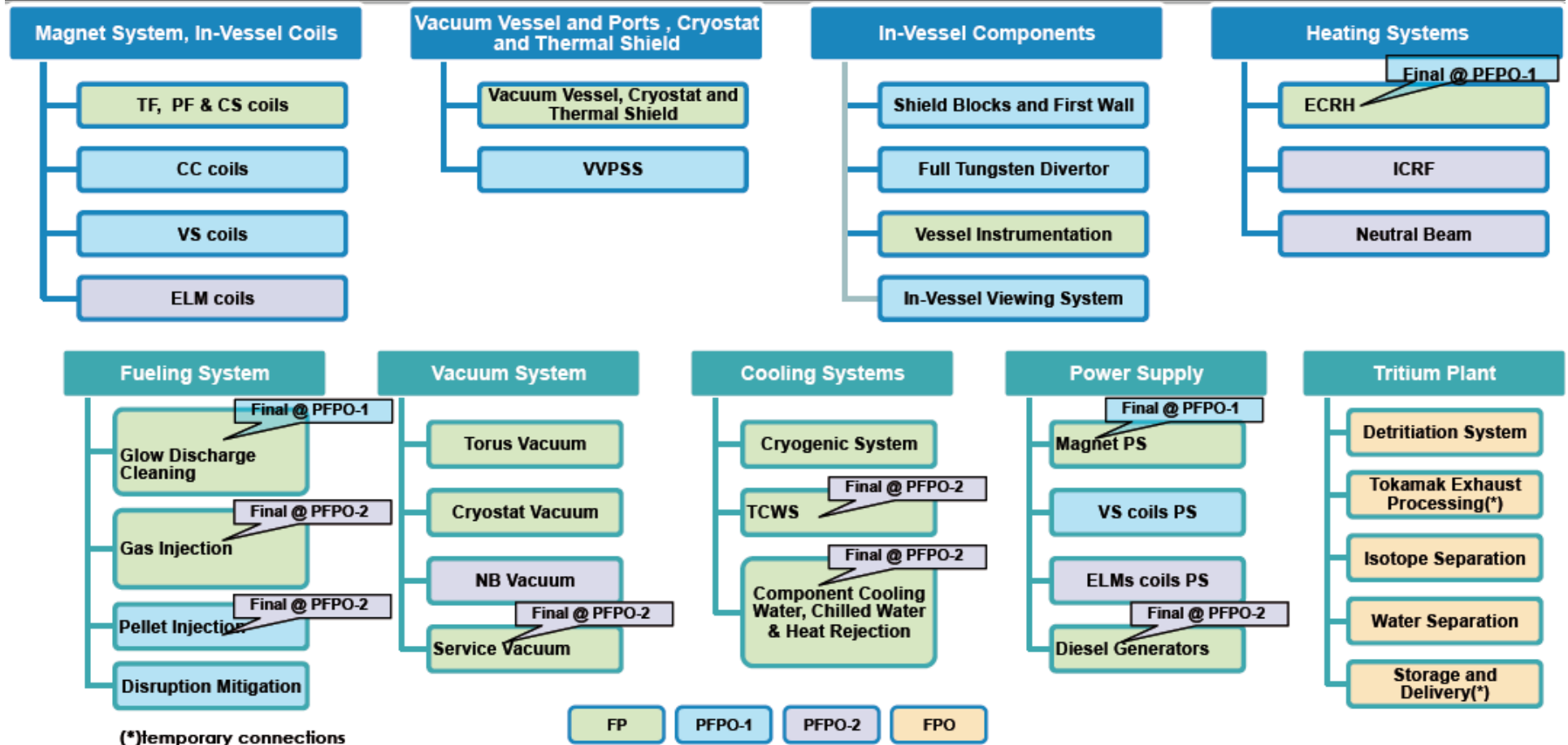
Due to the massive size of the ITER Tokamak components, as well as the intense neutron flux that will occur during operations, the ITER machine has required the development of cutting-edge robotics and remote handling tools, which will be used in both the assembly and operational phases.

Staged Approach to Operations

Configuration for each phase of Operation



Configuration for each phase - overall



Example:

Additional Diagnostics for PFPO-1

55.A8	Fibre Optic Current Sensor
55.AJ	High Frequency Sensors
55.AL/AO	Divertor Coils
55.AM	Divertor Shunts
55.AN/AP	Divertor & Blanket Rogowskis
55.B3	Microfission Chambers
55.B4	Neutron Flux Monitor Systems
55.B8	Neutron Activation System
55.BC	Divertor Neutron Flux Monitors
55.BF	Tangential X-Ray
55.BV	Neutron Calibration (2.5 MeV) [Partial]
55.BT	Neutron Facility Area
55.C1	Core Plasma Thomson Scattering (partial)
55.C5	Toroidal Interferometer Polarimeter
55.D1	Bolometry System

- **Emphasis in measurement capability:**

- plasma control (inc disruptions)
- investment protection
- basic plasma parameters

55.E2	H-Alpha Visible
55.E4	Divertor Impurity Monitor
55.E5	Core Imaging X-ray Spectrometer
55.E6	Visible Spectroscopy Reference System
55.E7	Radial X-Ray Camera
55.EG	VUV Divertor
55.EH	Vacuum UltraViolet Edge
55.EI	X-Ray Crystal Spectroscopy Edge
55.F1	Electron Cyclotron Emission
55.FA	Density Interferometer Polarimeter
55.G1	Vis/IR Eq Ports (remainder of system)
55.G2	Thermocouple (divertor)
55.G3	Pressure Gauges
55.G4	Residual Gas Analysers
55.G6	Divertor IR Thermography
55.G7	Langmuir Probes
55.GA	Vis/IR Upper Ports
55.GD	First Wall Samples
55.GE	Flow Monitor
55.GG	Calorimetry (for testing with aux. heating inputs)

Black = functional

Orange = not functional* (captive)

Blue = “upgrade”

Research Plan within Staged Approach

- **ITER Research Plan Workshop held during 26-28 July with participation of experts from Members' fusion communities**
- **Workshop participants requested to analyze key activities required to develop the research programme following First Plasma to:**
 1. commission all required auxiliary systems with plasma to full performance (with pulse durations appropriate to the programme requirements)
 2. develop the experimental capability required to achieve initial DT fusion power production at levels of several hundred MW
- Workshop participants also requested to analyze:
 - consistency of system availability and planned experimental programme
 - estimates of the experimental time required
 - experimental/ operational issues requiring further analysis within the ITER R&D programme to support the further development of the Research Plan
 - risks to the Research Plan and possible mitigation measures

Research Plan Structure and Activities

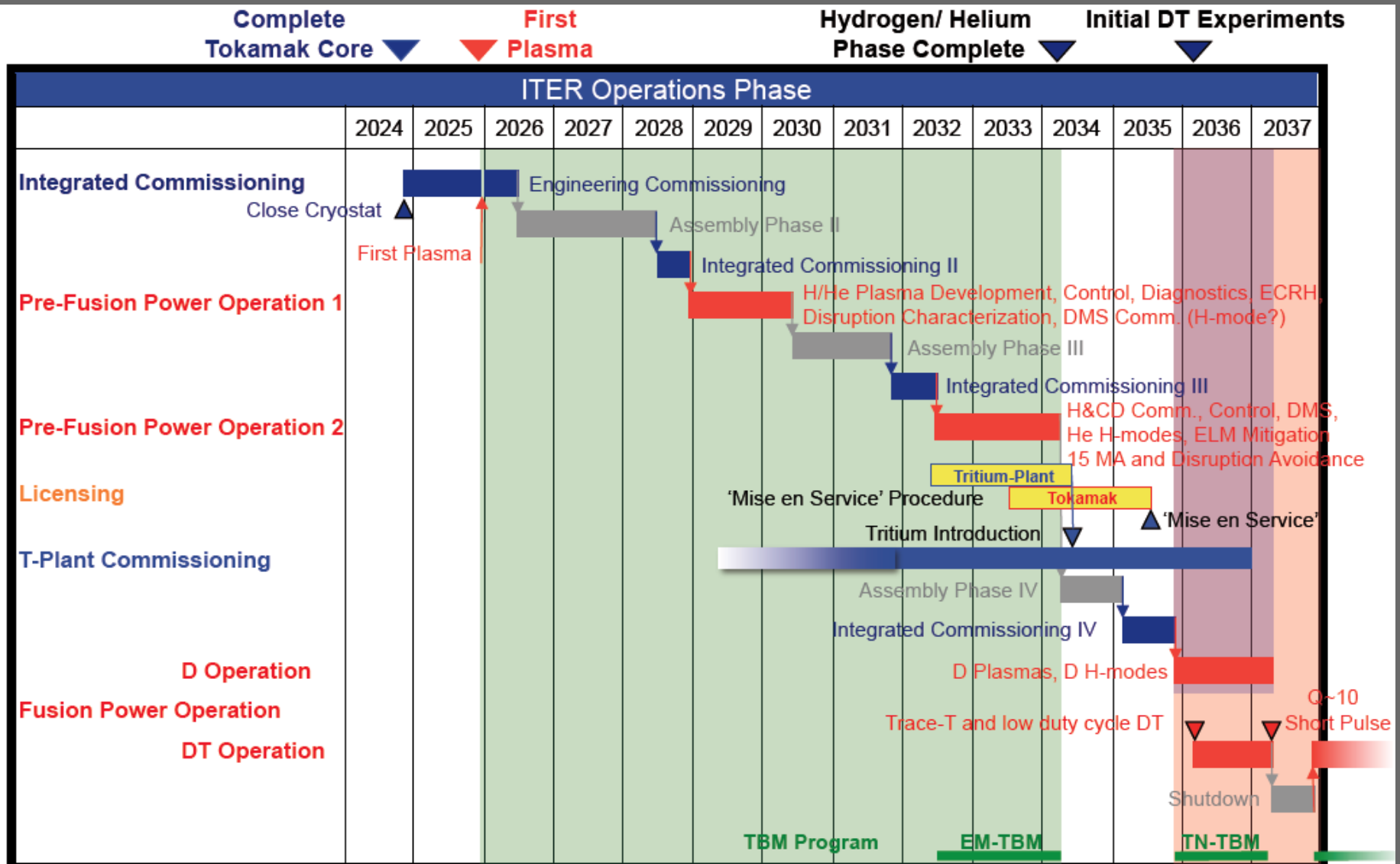
1. Pre-Fusion Power Operation (PFPO):

- First Plasma: nominal 100 kA/100 ms
- plasma operation to ~ 3.5 MA to establish initial divertor operation
- disruption loads, disruption detection, avoidance and mitigation
- development of plasma operation to ~ 7.5 MA/ 2.65 T
- possible option for operation at 5 MA/1.8 T (allowing early H-mode access?)
- H-mode operation and ELM Control
- demonstration of 15 MA/ 5.3 T operation

2. Fusion Power Operation (FPO):

- development of deuterium H-modes and preparation of DT scenarios
 - initial DT operation to short-pulse $Q \sim 10$
- ⇒ leads on to long pulse operation with inductive pulses of ~ 400 s at $Q=10$ and non-inductive operation aiming to achieve $Q \geq 5$ for periods ~ 3000 s

Overview of ITER Research Plan



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First Plasma

1. Integrated Commissioning:

- integrated commissioning of required plant systems (central control systems, power supplies, cooling/baking, vacuum, cryogenics etc)
- integrated commissioning of Magnet systems to level required for FP (nominally 50% maximum current)
- magnetic diagnostic calibration
- integrated commissioning of ECRH, diagnostics, fuelling, GDC, PCS systems

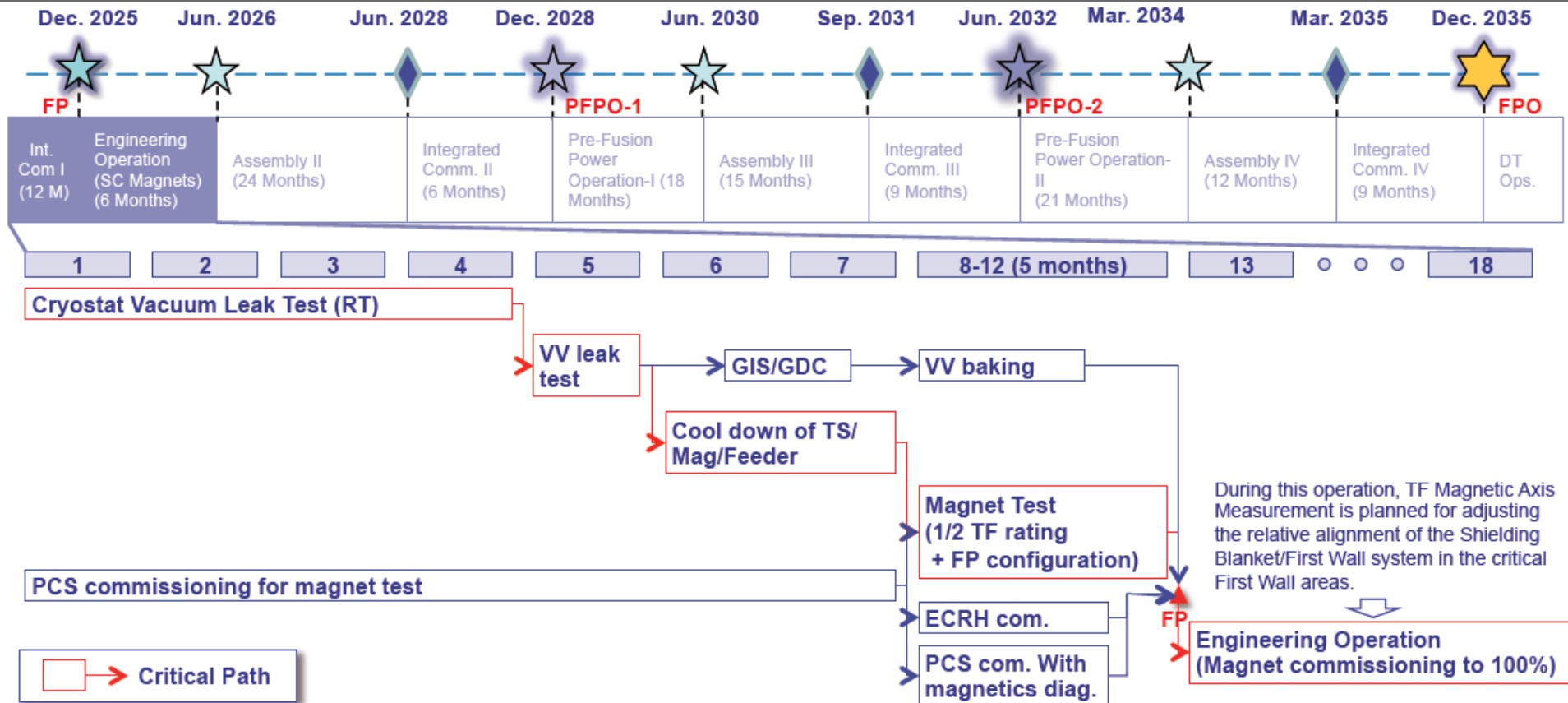
2. First Plasma:

- 100 kA/ 100 ms milestone

3. Engineering Operations (~6 months):

- performance tests of all Magnet systems to full current
- magnetic axis alignment measurement
- if opportunity arises, 1 MA circular limiter plasma demonstration

Integrated Commissioning I and Engineering Operations



Pre-Fusion Power Operation 1 - I

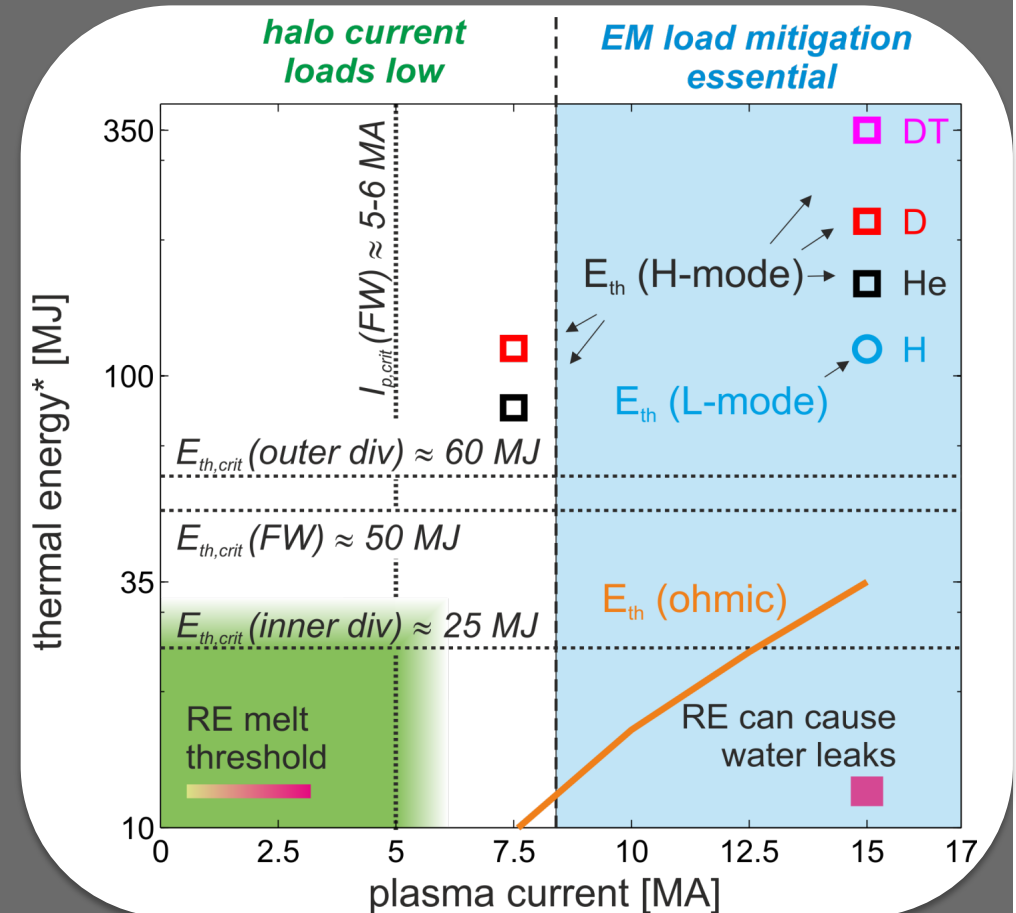
- **Main elements of experimental programme during PFPO-1:**
 - development of plasma control capability (PCS), including CIS/CSS plasma-related functions:
 - commissioning of plasma magnetic control
 - commissioning of core plasma density and impurity control
 - commissioning of blanket first wall protection system
 - initial commissioning of divertor heat flux control capability
 - commissioning of disruption prediction, avoidance and disruption/runaway electron mitigation systems
 - exploitation of VS coils and Correction Coils; possible early functional tests of ELM Control coils
 - commissioning of ECRH to full power in all launchers
 - development of plasma scenarios for robust operation up to perhaps 10 MA (with B_T over range 1.8 – 5.3 T)

Pre-Fusion Power Operation 1 - II

- **Critical first step is commissioning of plasma magnetic control:**
 - foreseen to occur in 3 steps in H/He (each step ~ 60 days):
 - $I_p \sim 3.5$ MA ($B_T = 2.65$ T, $I_{CS1} \approx 20$ kA)
 - $I_p \sim 5$ MA ($B_T = 2.65$ T, $I_{CS1} \approx 30$ kA)
 - $I_p \sim 7.5$ MA ($B_T = 2.65$ T, $I_{CS1} \approx 30$ kA)
- **Main elements of programme in H/He for study of 7.5 MA L-mode plasmas (possibly higher current depending on operational time):**
 - analysis of disruption loads
 - development of disruption detection/ prediction capability and commissioning of disruption mitigation capability:
 - commissioning of P_{EC} to 20 MW and pulse length to beyond 50 s
 - development of 7.5 MA/2.65-5.3 T plasma scenarios with flat-top of ~ 50 s
 - study of L-mode energy and particle transport, MHD stability, divertor physics in 7.5 MA plasmas

PFPO-1 – disruption loads and mitigation

- Quantitative analysis of thermal and EM loads for unmitigated disruptions in ITER:
 - EM loads imply DMS essential above 8.4 MA
 - **Green**: operational space where no risk of melting of W-divertor
 - **Magenta bars**: risks associated with RE loss to FW
 - **Orange line**: W_{th} for ohmic plasmas
- Extensive programme of disruption characterization, avoidance and mitigation throughout experimental phases



PFPO-1 – option for operation at 1.8 T

- **Option for low field operation (1.8 T):**
 - provisional analysis of TF coil inner leg wedging indicates that operation at $B_T < 2$ T is possible
 - initial plasma scenarios at 1.8 T (1/3 full field) have been generated - detailed load calculations confirm that plasma scenarios viable
- **Possible plasma operation scenario:**
 - plasma breakdown and effective heating requires second harmonic ECRH
 - possibility of dual frequency operation (170/ 104 GHz) of a tranche of gyrotrons (JA DA) under investigation
 - requires relatively minor modifications to ECRH transmission system
 - calculations of combined 2nd/3rd harmonic ECRH efficiency being launched
 - if viable, such an option would provide access to promising operational scenarios

PFPO-1 – option for operation at 1.8 T

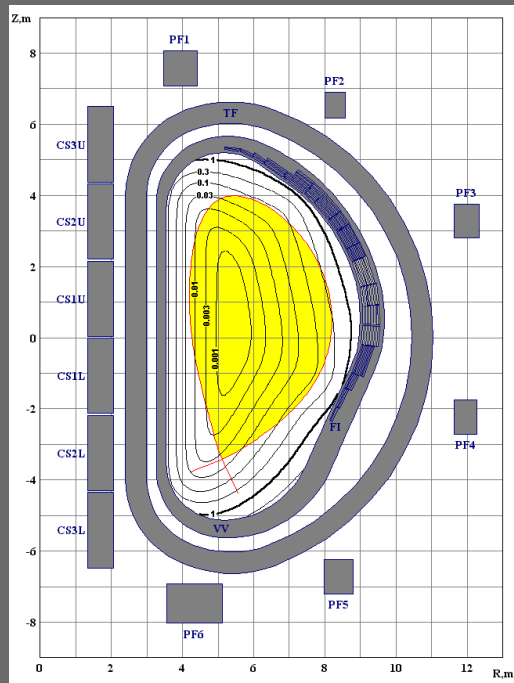
‘Martin’ scaling

$n_{e,min}$ (10^{20} m^{-3})	B_T (T)	S (m^2)	$P_{th} - \text{H}_2$ (MW)	$P_{th} - \text{He}$ (MW)	$P_{th} - \text{D}_2$ (MW)	$P_{th} - \text{DT}$ (MW)
0.16	1.8	683	20	10 - 15	10	8
0.25	2.65	683	37	19 - 28	19	15
0.5	5.3	683	106	53 - 80	53	43

- **Potential plasma scenario at 5 MA/ 1.8 T ($q_{95} \sim 3$):**
 - in helium plasmas, this scenario would permit access to H-mode transition studies if 20 MW of ECRH can be coupled efficiently to plasma
 - in PFPO-2, hydrogen H-modes might be accessible if, say, 50% of ICRF power can be coupled (2nd harmonic H majority)
 - in D/DT operation, this scenario would provide access to H-mode at lower stored energy (and ELM amplitude)

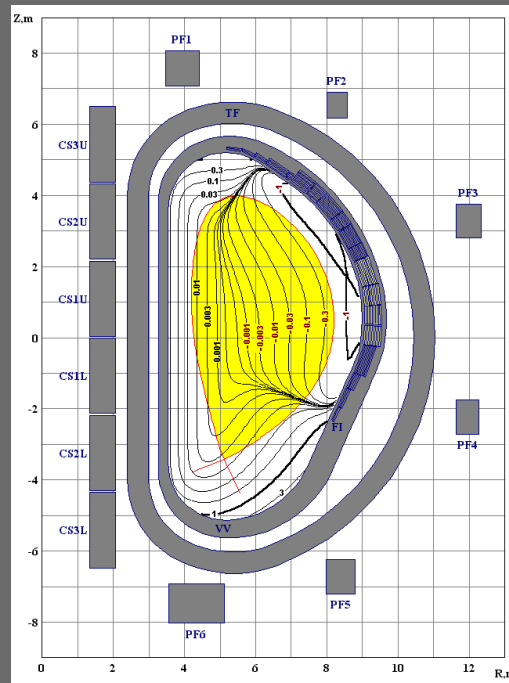
PFPO-1 – possible scenarios at 1.8 T

TF ripple in vacuum vessel regular sectors



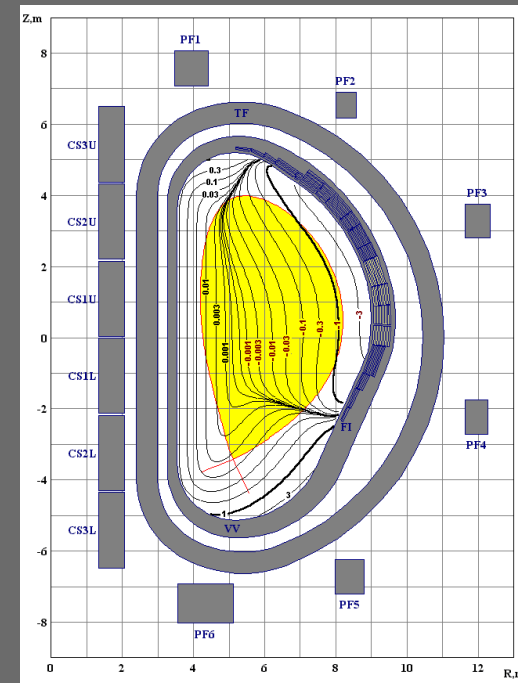
$$B_t = 5.3 \text{ T}$$

$$\delta_{max} = +0.34\%$$



$$B_t = 2.65 \text{ T}$$

$$\delta_{max} = -0.54\%$$



$$B_t = 1.8 \text{ T}$$

$$\delta_{max} = -1.28\%$$

High level of ripple at 1.8 T may impact confinement quality

PFPO-1 – possible scenarios at 1.8 T

- **Advantages if 1.8 T scenarios can be exploited:**
 - low power threshold for H-mode access
 - operation at $q_{95} \approx 3$
 - investment protection during commissioning
 - potential scenario for effective EC heating of plasmas (2X/3X)
 - H-mode operation at 1.8 T in PFPO-2 (hydrogen?) and FPO campaigns
- **Issues to be further considered/ analyzed:**
 - EC start-up assist in 3X operation
 - impact of TF ripple on H-mode performance (and fast particle losses if ICRF/HNB used)
 - low density operation and H-mode access
 - lower performance H-modes (e.g. TF ripple) may limit scope for physics studies, development of MHD control, etc

PFPO-1 – options for ICRF exploitation

- Installation of one ICRF antenna to couple 10 MW to the plasma, increasing the total auxiliary heating to 30 MW (20 MW ECRH + 10 MW ICRF)
- Allow early commissioning of ICRF system for optimization studies (coupling, etc.)

- **Half-field operation (2.65 T):**

- H plasmas → dominant electron absorption (very broad)
- He plasmas → fundamental H minority, good absorption

- **Third-field operation (1.8 T):**

- H plasmas → 2nd harmonic H majority, good absorption
- He plasmas → dominant electron absorption.

Main ion	B _T (T)	P _{L-H} (MW)	Good IC scenario	H-mode
H	2.65	37	no	no
He		28	yes	possibly
H	1.8	20	yes	yes
He		15	no	probably

Caveat: -1.28% ripple at 1.8 T

Pre-Fusion Power Operation 2 - I

- **Main elements of programme in H/He for study of 7.5 MA H-mode and 15 MA L-mode plasmas:**
 - commissioning of HNB (33 MW), ICRF (20 MW) and DNB with plasma
 - continued development of plasma control capability:
 - feedback control of H&CD systems
 - initial commissioning of non-axisymmetric and profile control schemes
 - termination scenarios in H-mode and at high plasma current
 - extend capability for disruption prediction, avoidance and mitigation
 - demonstration of divertor heat flux control at higher P_{aux}
 - establishment of H-mode plasmas at 7.5 MA/ 2.65 T (primarily in He) and development of ELM control as internal coils commissioned
 - demonstration of 15 MA/5.3 T L-mode plasmas at highest P_{aux}
 - characterization of key aspects of PWI in ITER environment

Pre-Fusion Power Operation 2 - II

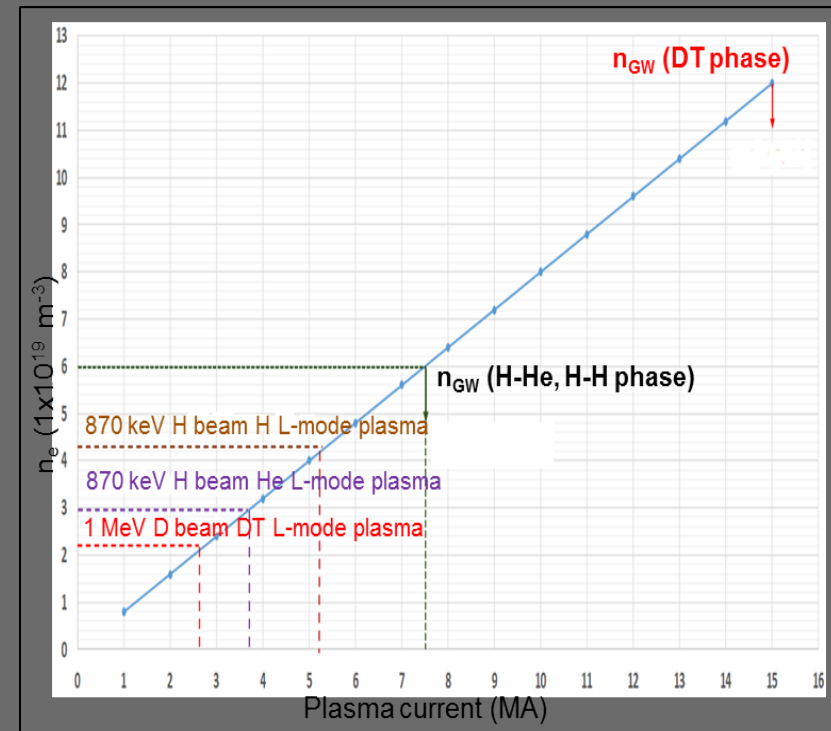
- Commissioning of H&CD systems to full power/ ~50 s:

- commissioning of HNB (33 MW) (and DNB) with plasma

- following off-line beam-line commissioning during Integrated Commissioning III
- must be adapted to shinethrough limits
- gradual increase in injected pulse length as ducts conditioned/ shinethrough monitored

- commissioning of 10 - 20 MW ICRF with plasma

- requires antenna conditioning in vacuum
- significant commitment to antenna coupling/ tuning of matching systems
- tests of antenna phasing, frequency sweeping, power modulation
- gradual extension of pulse length



HNB shinethrough limits

Pre-Fusion Power Operation 2 - III

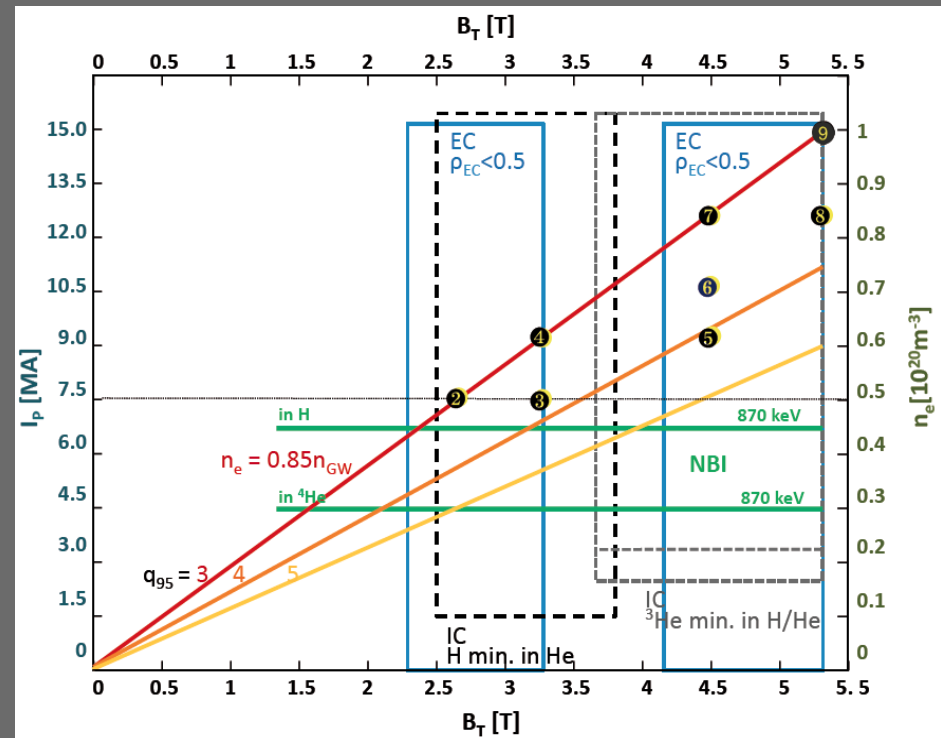
- **H-mode operation and ELM control in H/ He plasmas:**
 - establishment of H-mode at 7.5 MA/ 2.65 T (primarily in He):
 - determination of H-mode access conditions at ITER scale in He – and in H, if circumstances favourable
 - commissioning of ELM control coils and demonstration of ELM suppression with magnetic perturbations
 - H-mode characterization in controlled ELM regime
 - investigate density and impurity control, ELM heat loads, etc
 - investigation of H-mode access in H:
 - operation at 5 MA/1.8 T could allow access to H H-modes if adequate P_{IC} can be coupled ($P_{LH} \sim 20$ MW) – or if low energy NBI possible (TBC)
 - alternatively, present results from devices with all-metal PFCs indicate reduction of P_{LH} by up to 30% possible – potential for access at 7.5 MA/2.65 T
 - if successful, significant H-mode programme in H viable – either as complement or replacement for planned programme in He

Pre-Fusion Power Operation 2 - IV

Revised concept for 15 MA scenario development with variable q_{95}

- Strategy for development of 15 MA scenario revisited:

- development of 15 MA scenario in H plasmas favoured to suppress marginal H-modes above 7.5 MA
- deviation from constant q_{95} has benefits via slower increase in disruption loads
- route towards higher I_p and B_T is developed to accommodate variations in ECRH resonance location
- breakdown must still be re-optimized at new B_T values



Pre-Fusion Power Operation 2 - V

- **Plasma-wall interaction studies increasingly significant in PFPO-2 (initiated in PFPO-1):**
 - ELM and quasi-stationary heat loads
 - investigation of possible localized (edge) melting, small-scale cracking of W PFCs
 - regular inspection by erosion monitor (Speckle interferometry) necessary
 - desirable to remove cassette for PFC inspection at end of campaign
 - quantitative fuel retention studies important – would benefit from trace-D experiments in H
 - T-removal studies
 - time required for divertor baking, conditioning discharges required
 - dust formation and properties
 - expect primary dust source to be melted Be from blanket first wall
 - regular monitoring of wall erosion/ damage by IVVS also essential

Fusion Power Operation - I

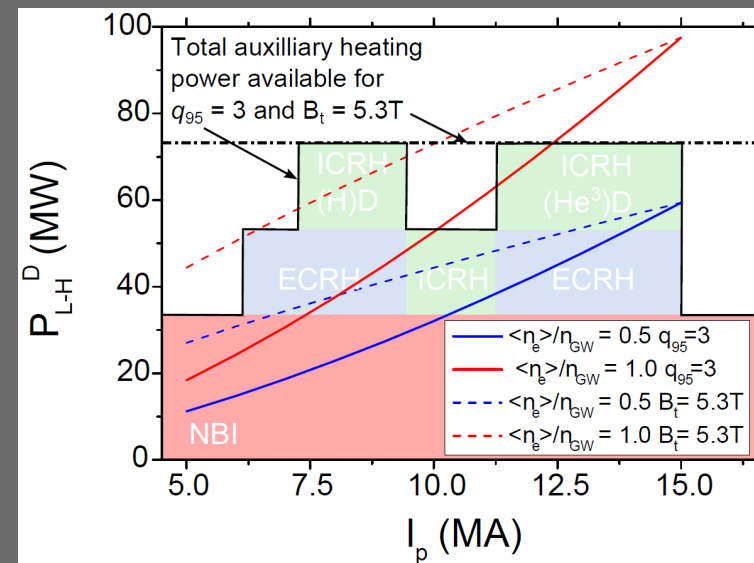
- **First period of FPO phase centres on machine recommissioning and D H-mode development:**
 - recommissioning of tokamak operation for D plasmas:
 - commissioning of H&CD system in D (HNB at 1 MeV D⁰)
 - re-optimize plasma magnetic scenario, if necessary
 - establishment of D H-modes in range 5 – 7.5 MA/1.8 – 2.65 T
 - re-establishment of ELM control techniques in D H-modes
 - studies of H-mode plasmas in D:
 - optimization of D H-modes at 7.5 MA/ 2.65 T
 - extension of 7.5 MA/2.65 T H-mode towards longer pulses and high power
 - trace-T experiments to initiate DT operation, investigate fuelling and fuel transport
 - extension of H-mode operation towards 15 MA/ 5.3 T, preparing DT scenarios
 - confirmation of reliable operation of DMS at high current and power

FPO – high current deuterium H-modes

'Martin' scaling

n_e (10^{20} m^{-3})	B_T (T)	S (m^2)	$P_{th} - H_2$ (MW)	$P_{th} - He$ (MW)	$P_{th} - D_2$ (MW)	$P_{th} - DT$ (MW)
0.5	2.65	683	61	31 - 46	31	24
0.5	5.3	683	106	53 - 80	53	43
1.0	5.3	683	175	88 - 132	88	70

- Based on 'Martin' scaling, H-mode operation at highest currents may/may not be possible:
 - depends on density control and power margin for high confinement
 - could be influenced significantly by all-metal PFCs



Fusion Power Operation - II

- **Development of fusion power production in DT:**

- development of DT H-mode operation at 7.5 MA/ 2.65 T:

- development of D H-mode operation with increasing T concentration (10 – 50%)
 - characterization of changing H-mode behaviour as T concentration increased
 - extension of H-mode operation towards high power and longer pulses (at least several tens of seconds)
 - adaptation of control functions to fusion power operation

- development of fusion power production in DT:

- development towards 15 MA/5.3 T DT H-mode operation, varying fuel mix to manage fusion power production and control issues
 - confirmation of reliable operation of DMS as fusion power increased
 - extension of plasma control capability in DT, including heat exhaust and fusion burn control
 - optimization of Q towards short-pulse $Q \sim 10$ operation at several hundred MW fusion power

Summary on Research Plan within Staged Approach

- **Key activities of the ITER Research Plan from First Plasma to initial DT operation have been re-analyzed within the framework of the ‘Staged Approach’:**
 - major activities adapted to match the staged availability of auxiliary systems
 - assuming acceptable hardware reliability, expected requirements for:
 - commissioning of necessary plasma control capability
 - H&CD systems
 - plasma scenario developmentappear compatible with available experimental time in PFPO phase
 - principal risks and key issues requiring further analysis identified
 - an option for operation at 1.8 T identified: implies some adaptation to the ECRH system, but would potentially allow early access to H-mode operation
 - option for including 10 MW ICRF capability in PFPO-1 and implications for plasma scenarios under study

ITER is moving forward!

<http://www.iter.org>

Backup Slides

Key ITER Physics R&D

Extensive Physics R&D programme in collaboration with international fusion community – addresses remaining design issues and preparation for Operations

- ✓ Effective disruption management essential to reliable operation
 - ✓ Addressing disruption detection, avoidance and mitigation
 - ✓ International collaboration on development of shattered pellet injector concept for disruption mitigation (IO-CT/ USIPO/ DIII-D/ JET)
- ✓ ELM control by magnetic perturbations, including spectral requirements and control of divertor heat loads
- ✓ Understanding impact of fuel and impurity transport on plasma performance in ITER
- ✓ Divertor and PWI studies:
 - ✓ Experimental and simulation studies to support specification of divertor monoblock shaping
 - ✓ Dust production, tritium retention and tritium removal

Coordinating ITER Physics R&D



**First ITER Scientist Fellows' Workshop
ITER HQ, September 2016**

- ✓ Emphasis on mobilization of fusion community:
 - ✓ Develop key R&D activities
 - ✓ Support Research Plan development
 - ✓ Prepare for efficient operation
- ✓ Mechanisms to integrate fusion community into ITER programme:
 - ✓ International Tokamak Physics Activity (ITPA)
 - ✓ IEA TCP on Co-operation on Tokamak Programmes (CTP)
 - ✓ MoUs with fusion facilities and academic institutions
 - ✓ ITER Scientist Fellows' Network