Introduction to ITER

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

Outline of talk

- ITER Mission, Basis, Goals, Scenarios and Overall Design
- ITER Project and *Overview of Construction Status*
- ITER Research Plan (IRP) and burning plasma physics
- Conclusions

ITER Mission, Basis, Goals and overall design

ITER Mission

To demonstrate the scientific and technological feasibility of fusion power as energy source for humankind based on D + T → ^{4}He + n (17.6 MeV)

P_{fusion} (^{4}He + n) = $P_\alpha + P_n > P_{external\text{-}heat}$

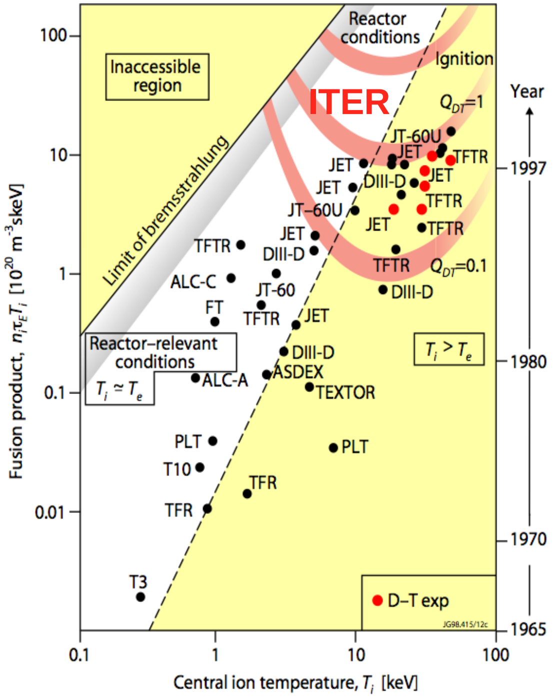
$Q = P_{fusion}$ (^{4}He + n)/$P_{external\text{-}heat}$

$P_{total\text{-}heat} = P_\alpha$ (^{4}He) + $P_{external\text{-}heat}$

$P_\alpha / P_{external\text{-}heat} = Q/5$

- To achieve high Q (> 5) requires hot (> 10 keV) plasmas with sufficient density that keep energy for sufficiently long time

$$n_i \tau_E T_i > 3\times10^{21}\ m^{-3}\ s\ keV$$

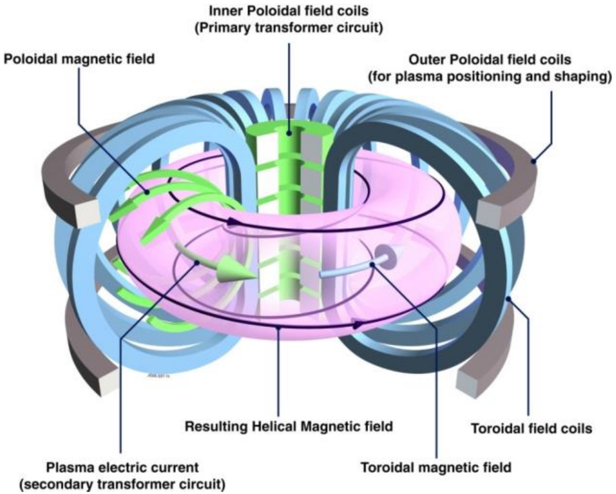


ITER Basis: Magnetic Confinement

At high temperatures required for fusion D and T are ionized ("Plasma") → hot DT can be contained by magnetic fields

Magnetic fields are used to :

- **Reduce thermal losses across magnetic field**
- **Provide stabilizing compression force to compensate hot plasma expansion**



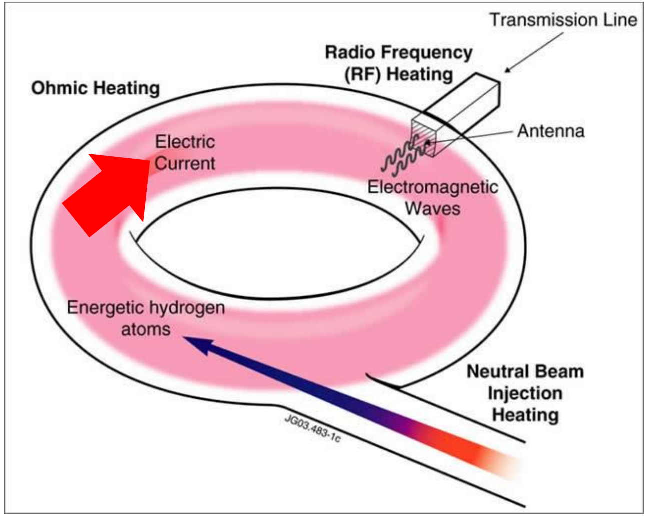
Tokamak

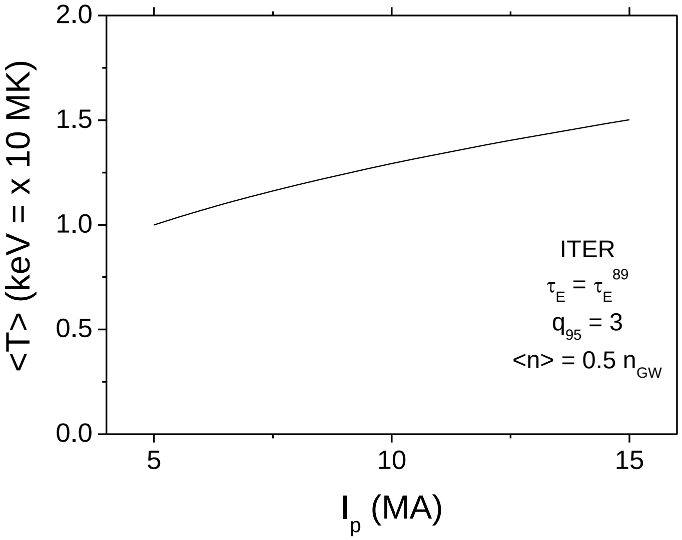
$$q = \frac{Toroidal\ turns}{Poloidal\ turns} \geq 2$$

ITER Basis: Plasma Heating

To achieve fusion power production T ~ 10 keV → Heating of Plasma is required :

- **Ohmic heating = $I_p^2 R_p$; $R_p \sim T^{-3/2}$ → insufficient**
- **Radio Frequency Heating**
- **Injection of energetic atoms**

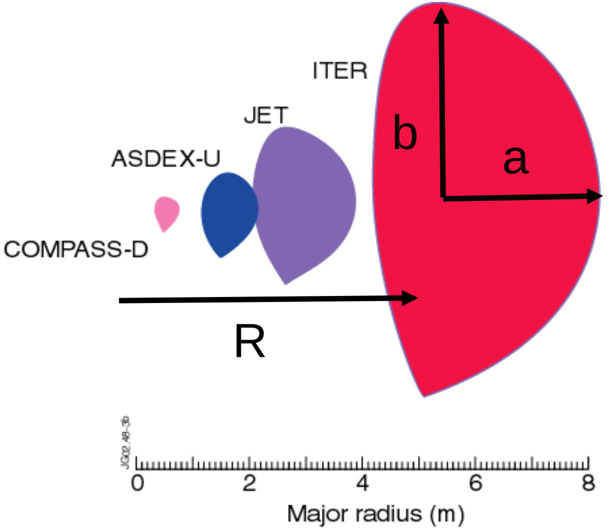


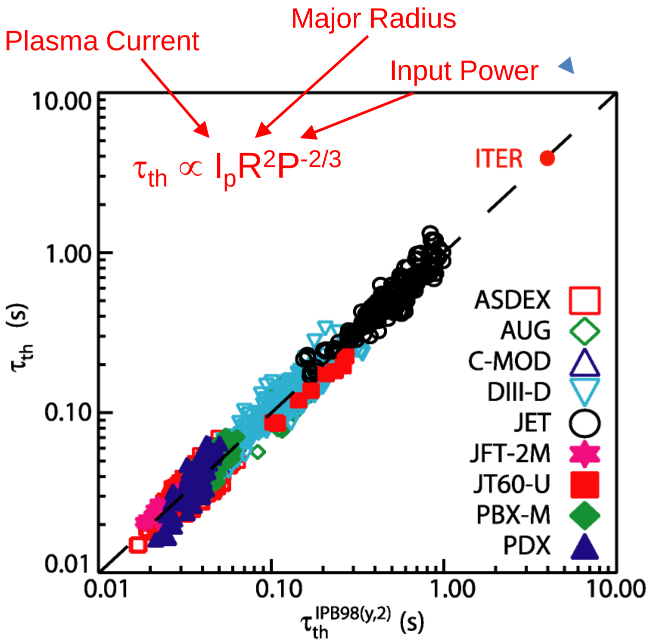


ITER Basis: Energy Confinement (τ_E)

- Energy confinement difficult to predict quantitatively → use scalings from experiments + plasma physics limits to dimension ITER to achieve its goals

$$\tau_{E,th}^{98(y,2)} = 0.144\, I^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.78} \quad \text{(s)}$$





$$q_{95} = 3$$

$$q_{95} = 2.5 \frac{a^2 B}{R I} f(\varepsilon, \kappa, \delta)$$

$$H_{98(y,2)} = \tau_{E,th}^{exp} / \tau_{E,th}^{98(y,2)}$$

ITER Goals

➢ **Pulsed operation:**

Q ≥ 10 for burn lengths of 300-500 s inductively driven current

→ **Baseline scenario 15 MA / 5.3 T**

$P_\alpha \geq 2\, P_{external\text{-}heat}$

➢ **Long pulse operation:**

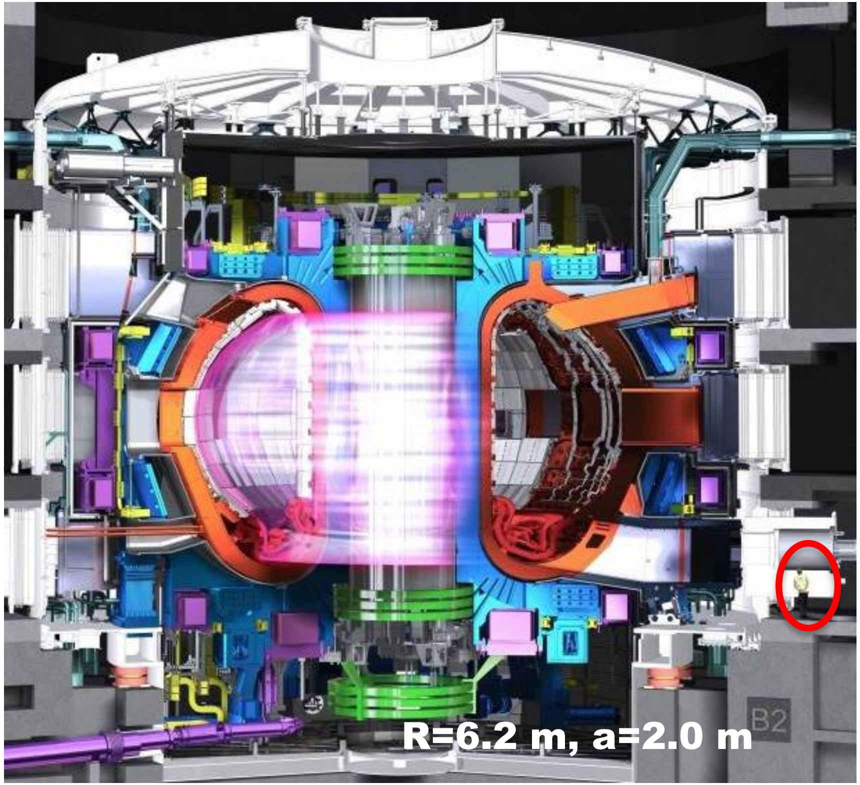
Q ~ 5 for long pulses up to 1000 s

→ **Hybrid scenario ~ 12.5 MA / 5.3 T**

➢ **Steady-state operation:**

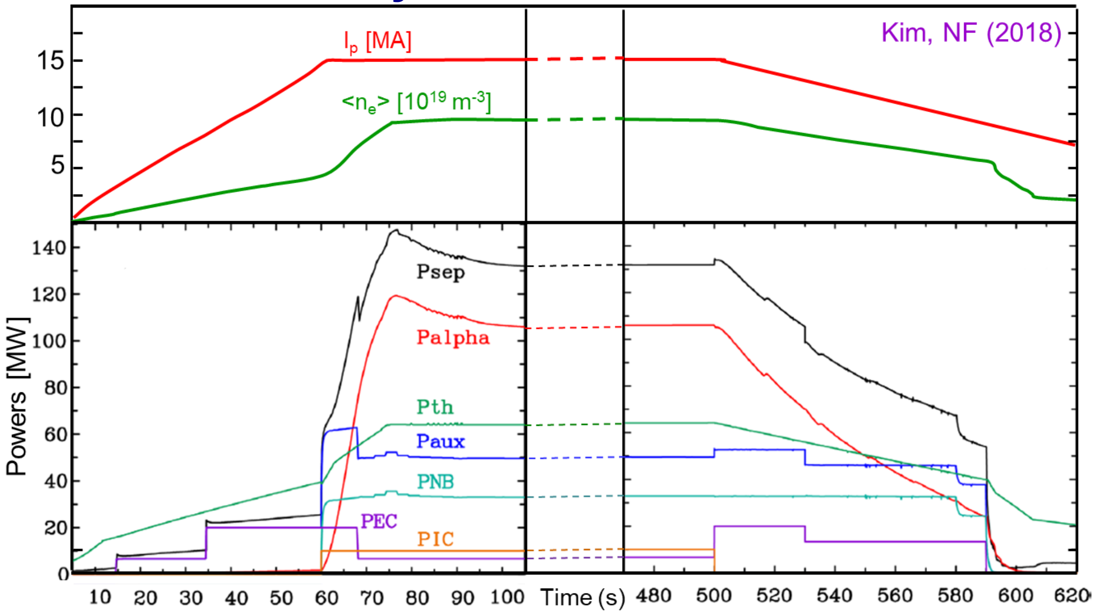
Q ~ 5 for long pulses up to 3000 s, with fully non-inductive current drive

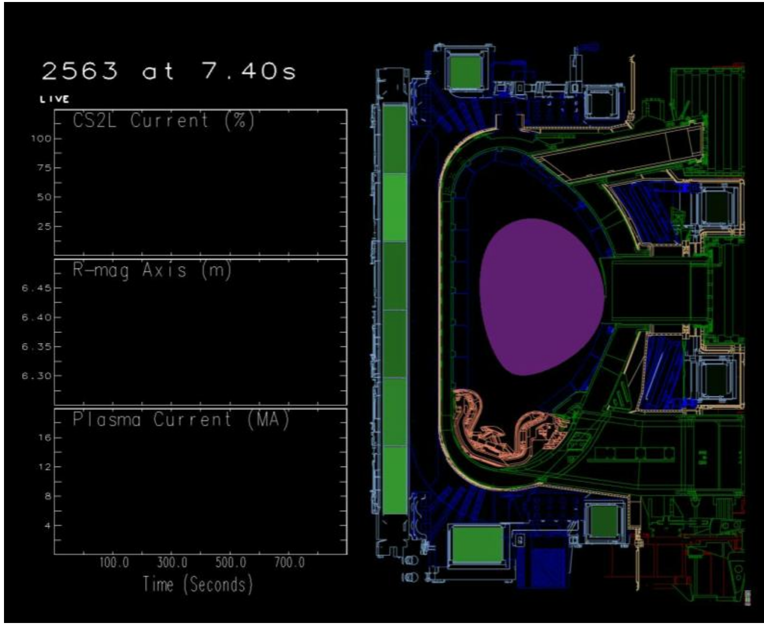
→ **Steady-state scenario ~ 10 MA / 5.3 T**



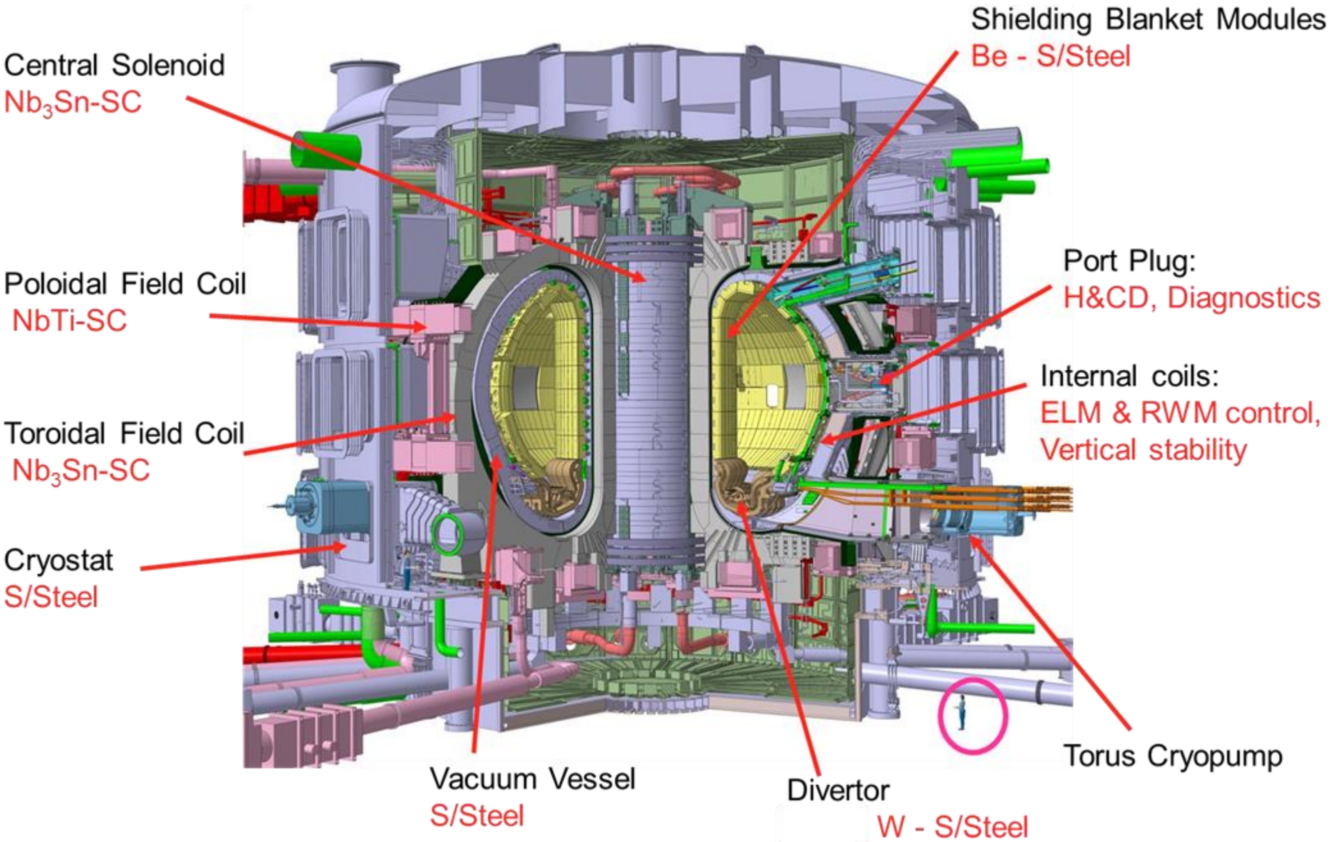
ITER Q = 10 scenario (300 – 500 s burn)

- Based on conventional sawtoothing H-mode with H_{98} = 1 → scenario used for the design of magnets and components (15 MA/5.3 T)
- $P_{aux} = P_{NBI} + P_{ECH}$ (+ P_{ICH}) ~ 50 MW → Alpha-heating dominant scenario with non-inductively driven current ~ 35%

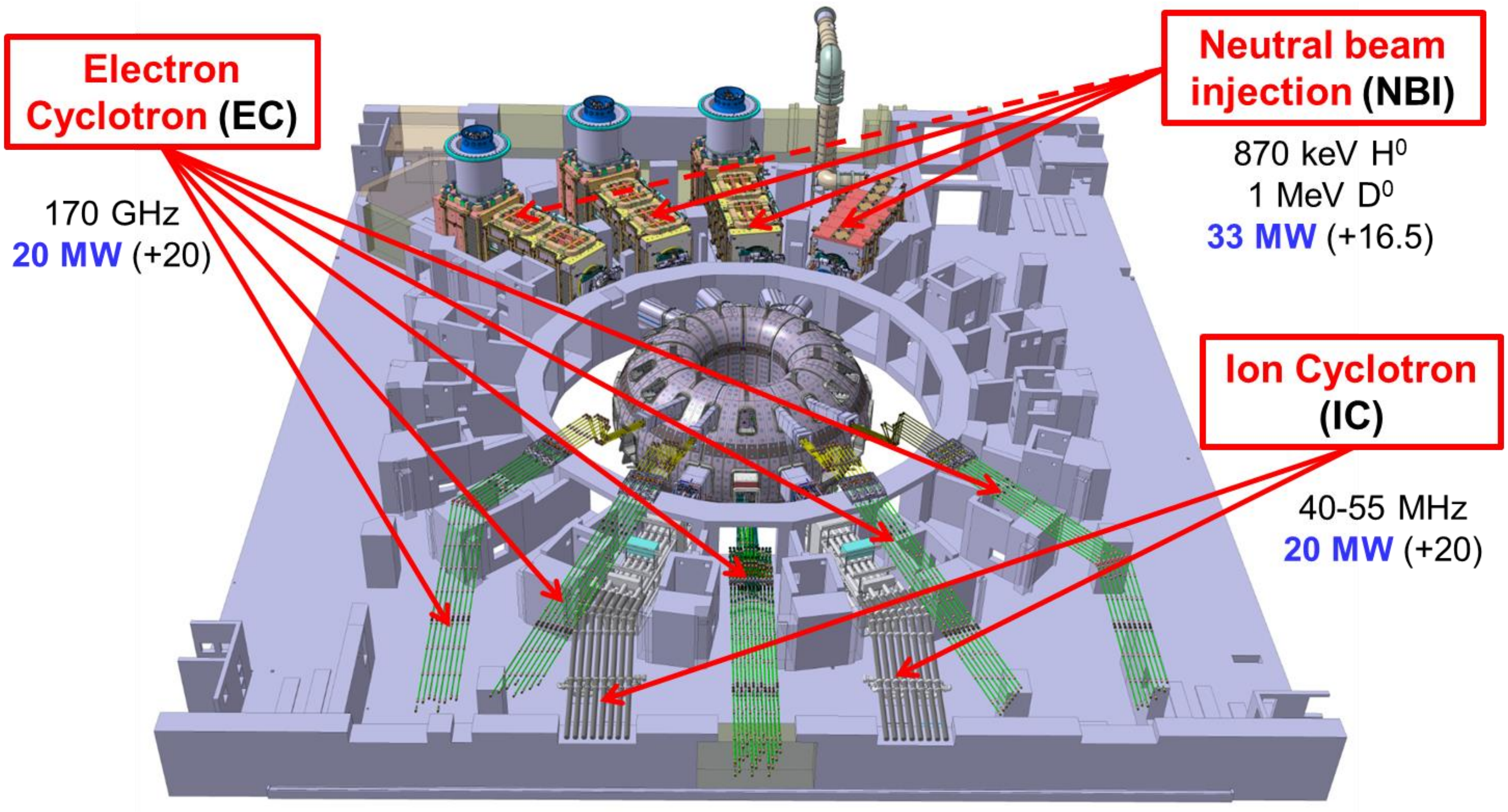




ITER Main Design Features

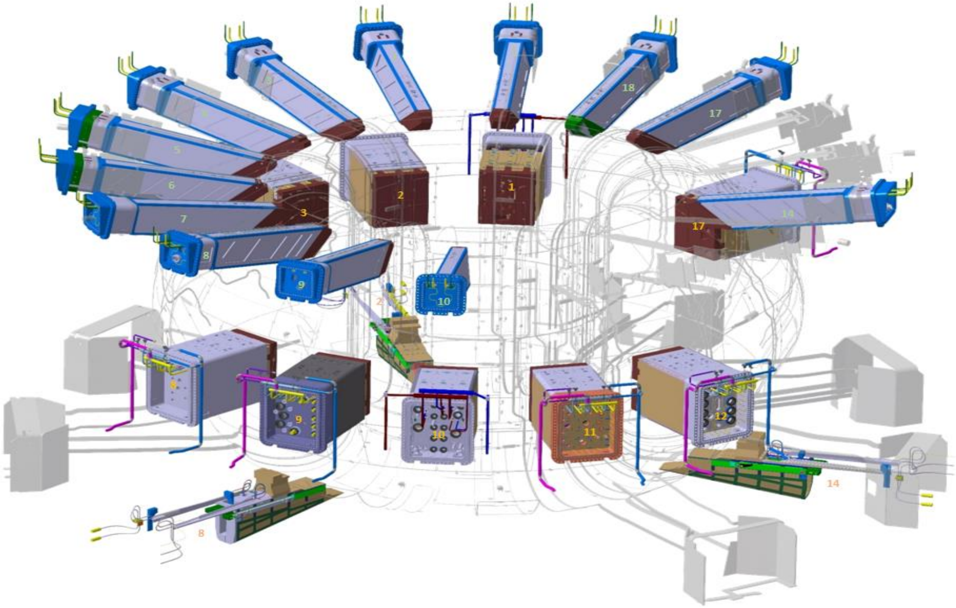


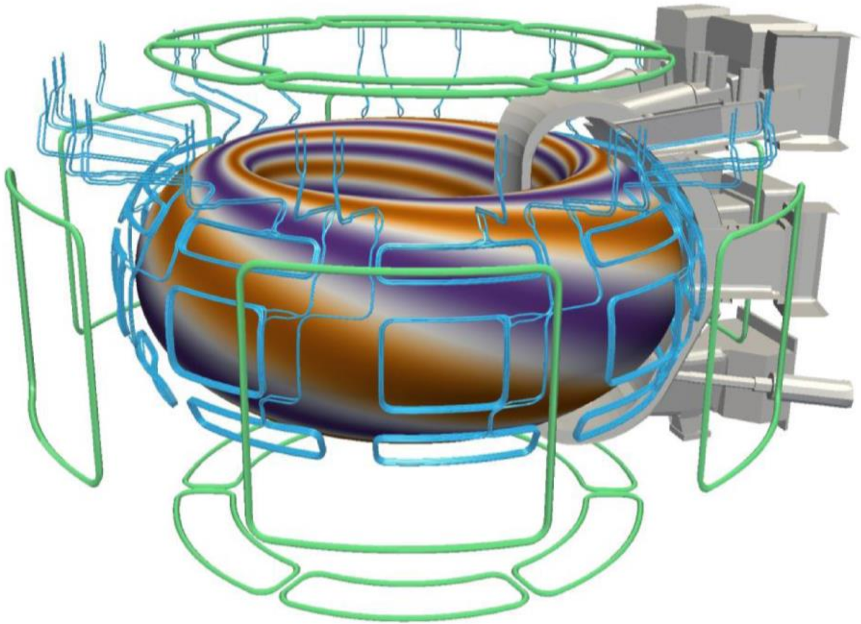
ITER Heating and Current Drive systems



ITER Diagnostics and 3-D coils (Error Field, ELM control)

- ❑ Diagnostics: ~ 60 instruments measuring ~ 100 parameters
- ❑ External error field correction coils + internal ELM control coils



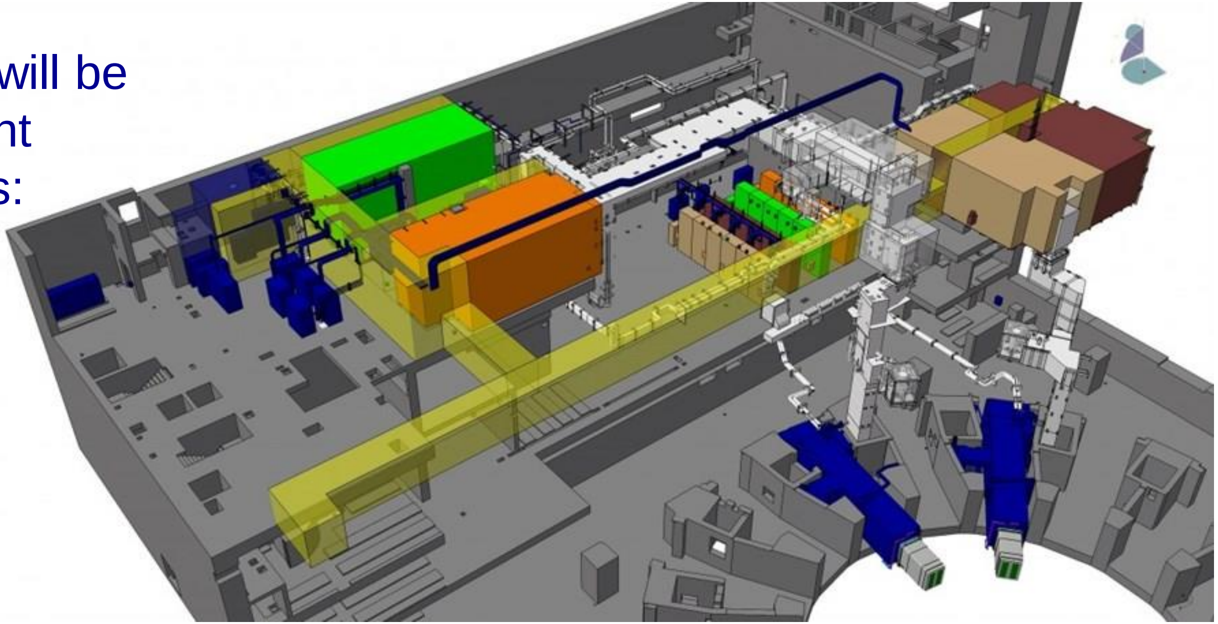


Tritium Breeding : Test Blanket Systems

Tritium not available in sufficient amounts for large scale nuclear fusion energy production → Tritium needs to be produced in-situ (n + Li)
T production schemes will de demonstrated in ITER (at small scale)

Different test blanket systems will be installed in ITER to test different combinations of design options:

- Liquid metal breeder
- Solid breeder
- Helium coolant
- Water coolant



ITER as a Project *and overview of Construction Status*

ITER

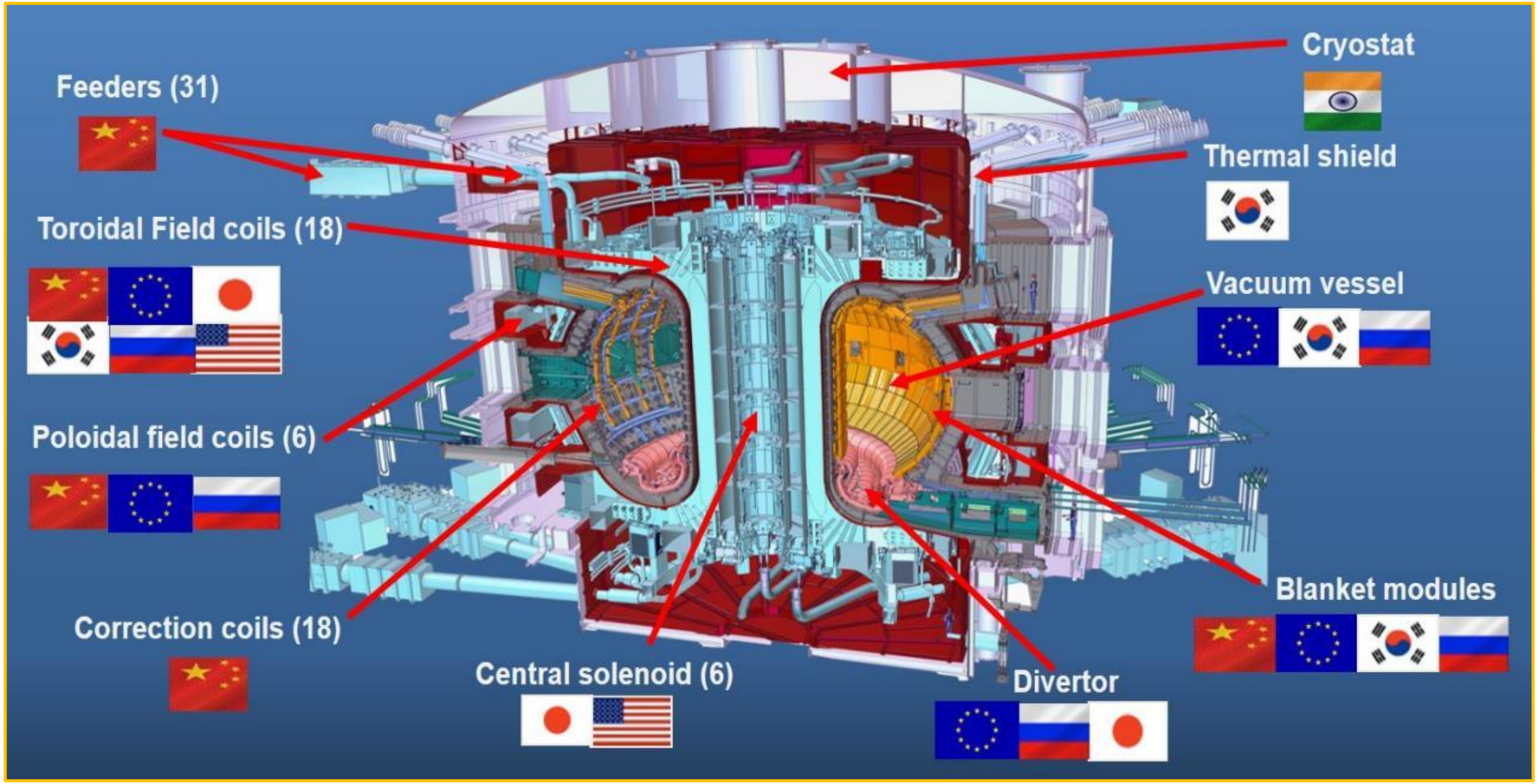
Global challenge, global response

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

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

China EU India Japan Korea Russia USA

Construction ITER – Who manufactures What ?



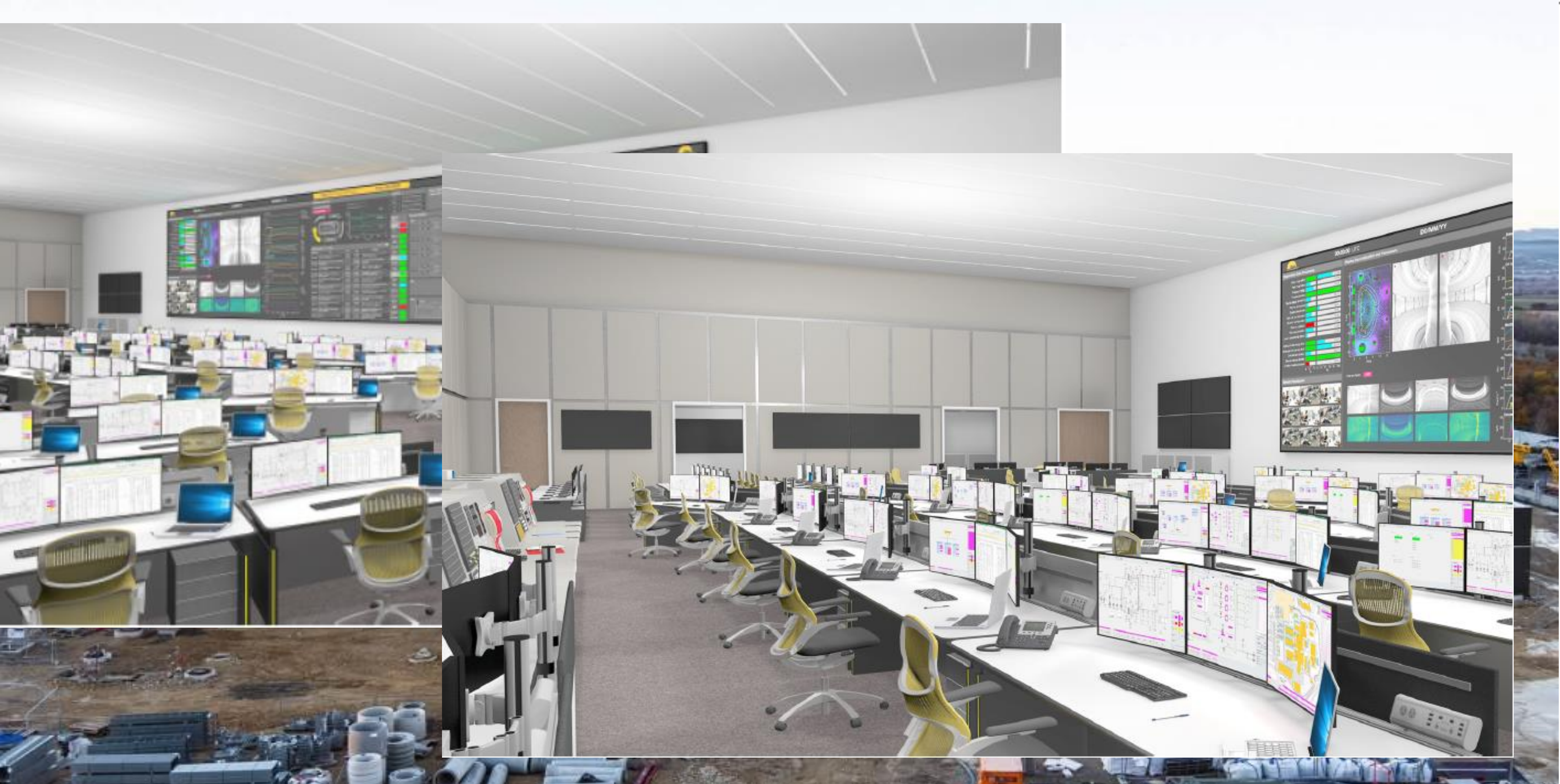
Many massive arrivals in 2020-23 (few shown)

ITER Site Construction Status

ITER construction site drone view

March 2023

ITER Control Room



Balance of plant

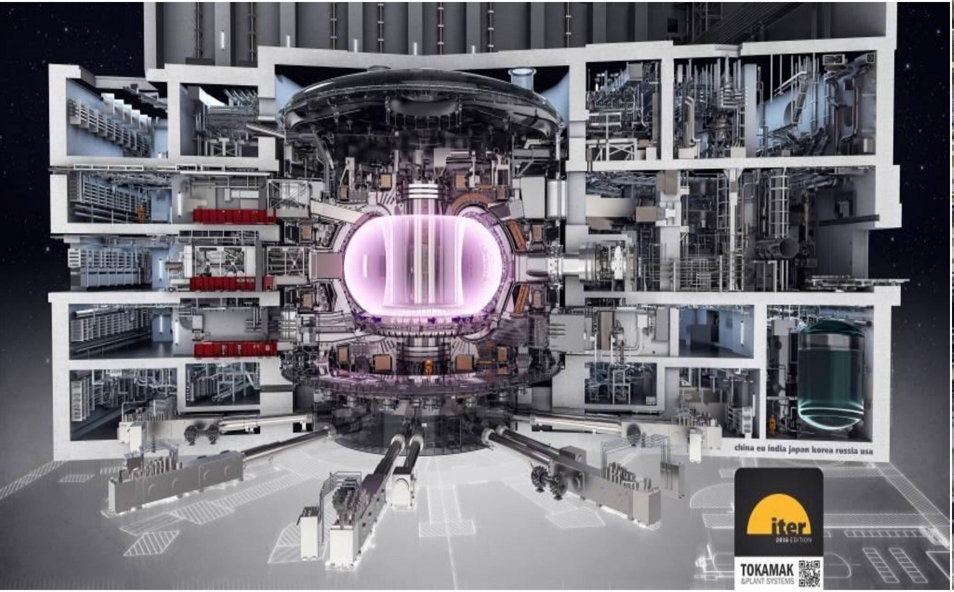
Towards commissioning

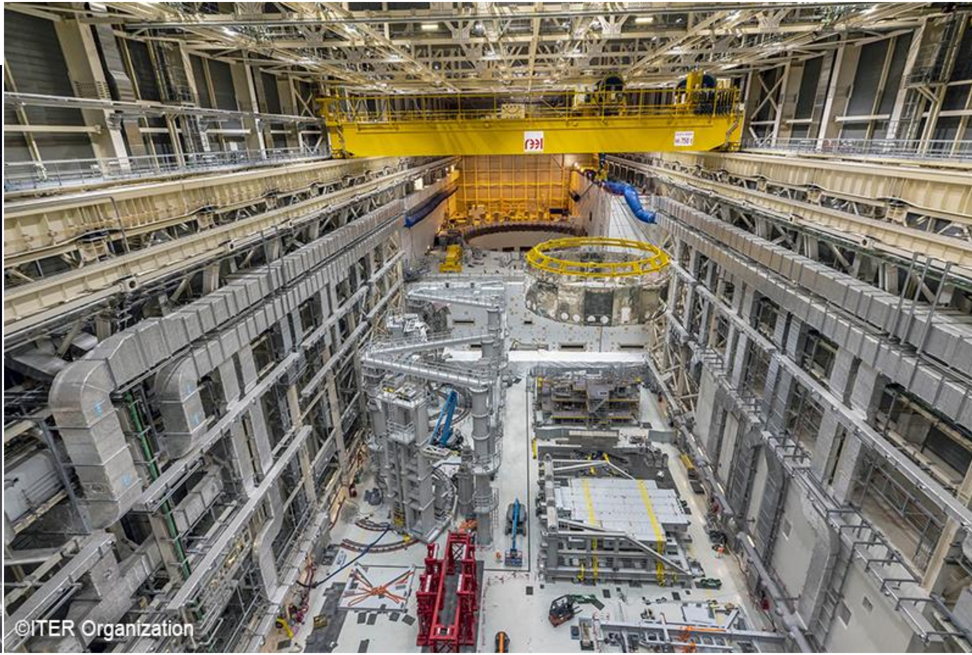
Cryoplant:
5 000 tonnes of equipment
LHe: 25 t
Cooling Power:
75 kW at 4.5 K (Helium)
1300kW at 80 K (Nitrogen)

ITER Tokamak Assembly Status

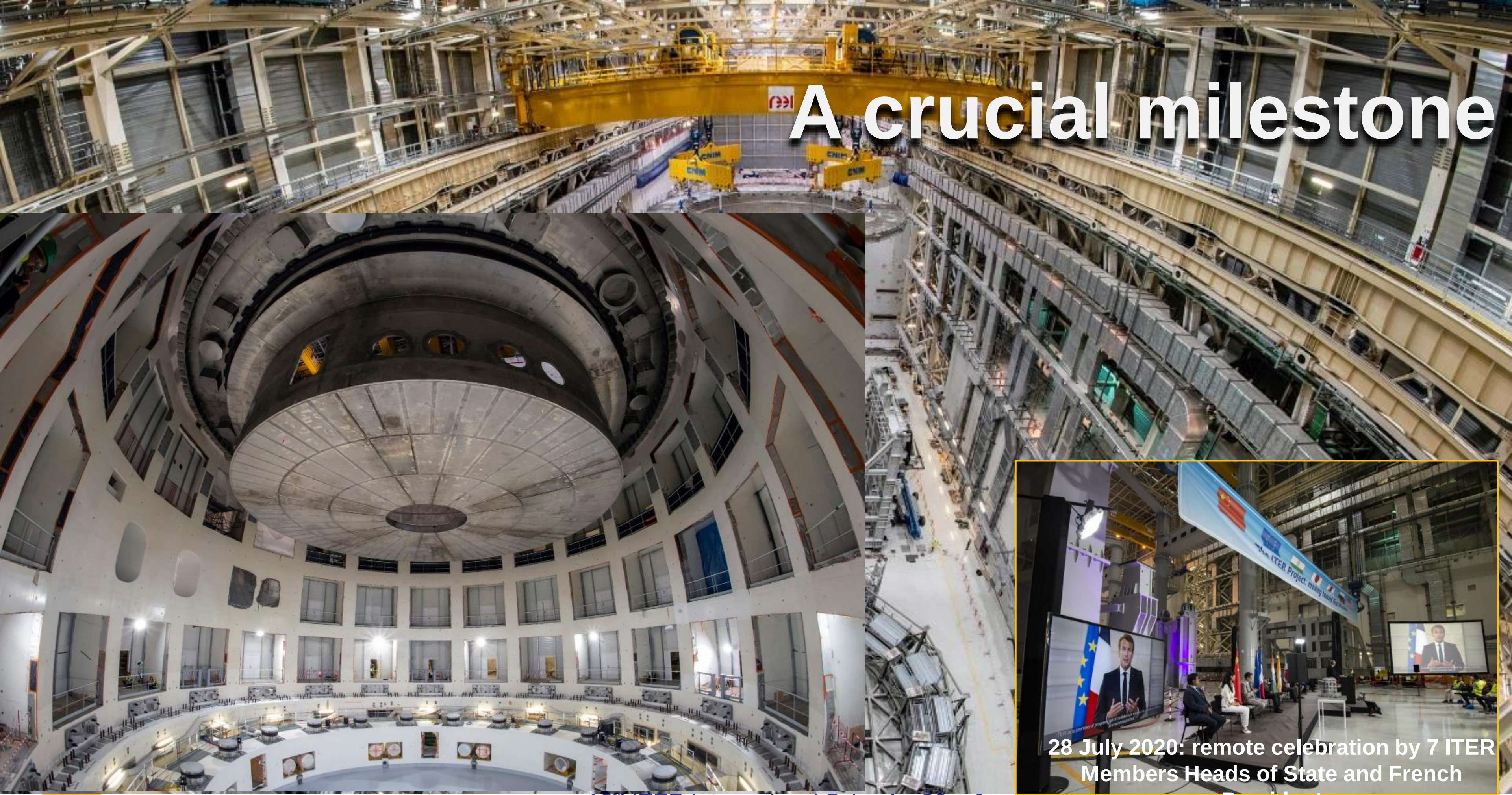
Assembly Hall and Tokamak building

- Tokamak components assembled in assembly hall and lifted by cranes into tokamak pit





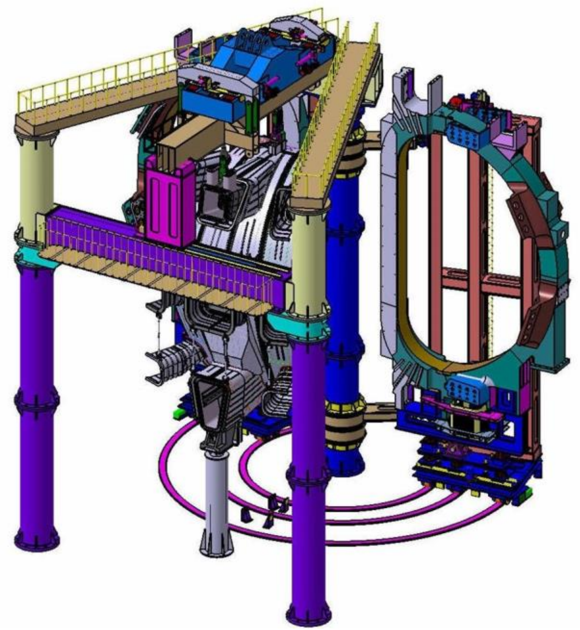
A crucial milestone



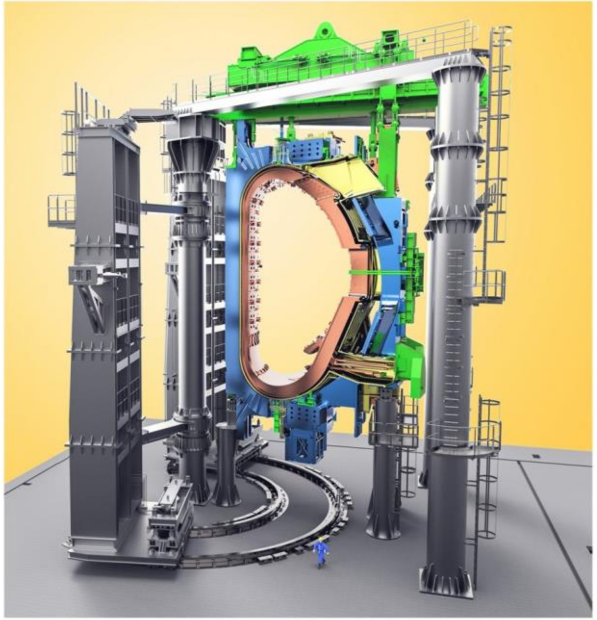
28 July 2020: remote celebration by 7 ITER Members Heads of State and French President

Sub-sector assembly

- Assembly of Vacuum Vessel, Thermal Shield and 2 Toroidal Field coils



TF Coil Assembly

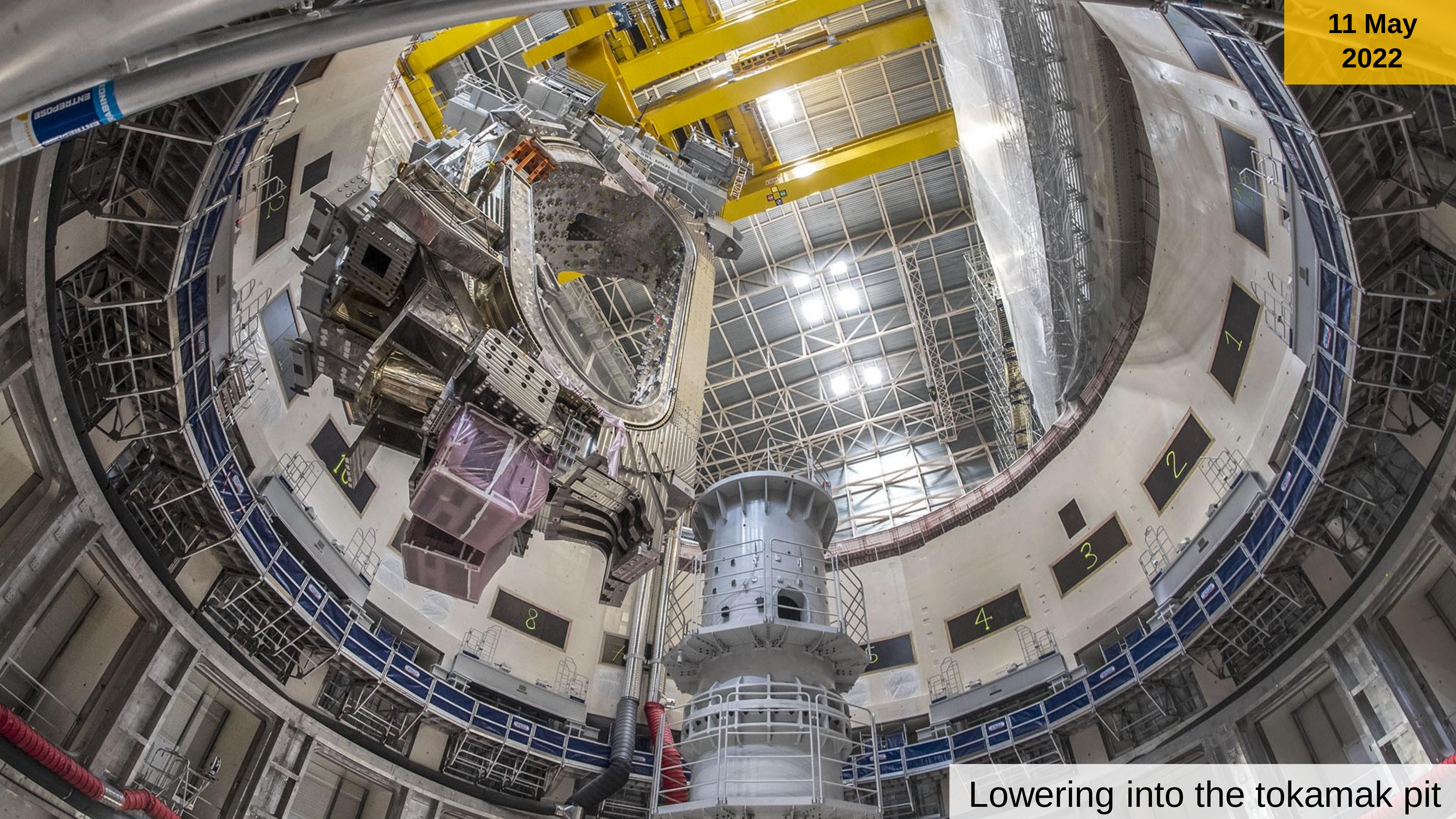


Finalized Sector Assembly before transfer to pit

11 May 2022

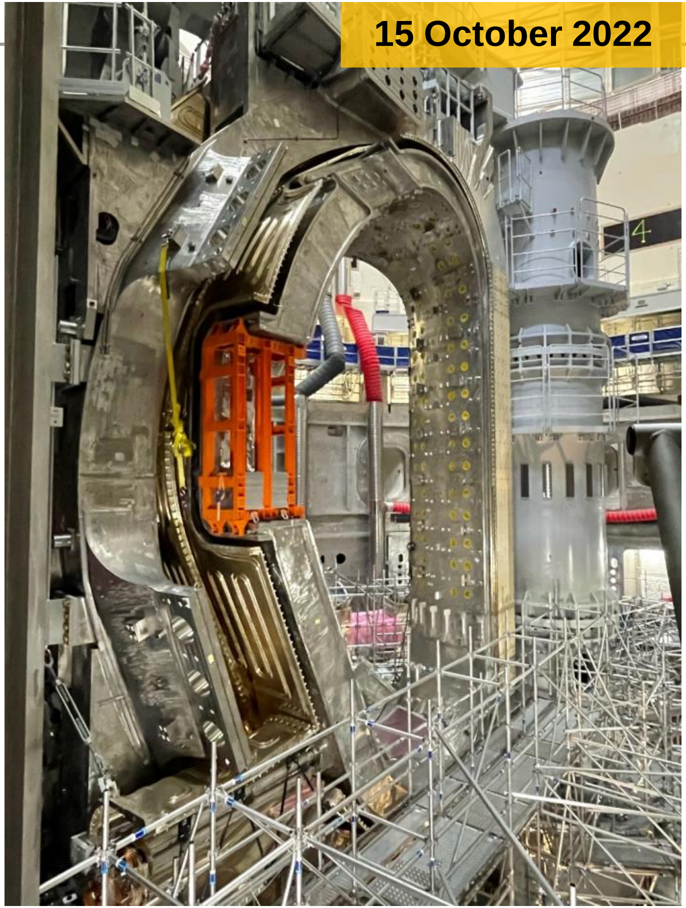
Sector 6 fully lifted out of SSAT-2 and rotated 90°

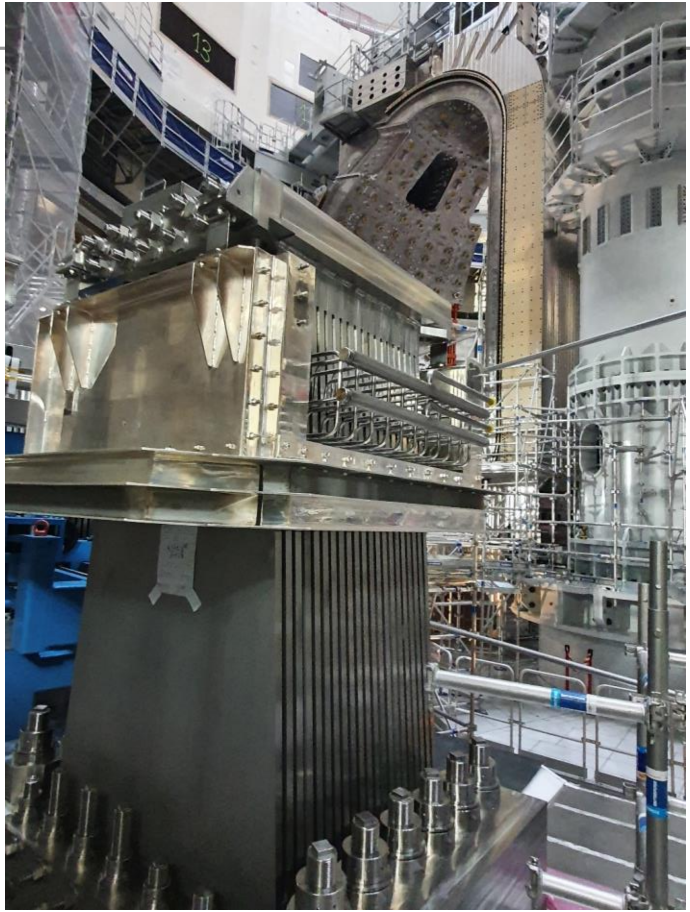
11 May
2022



Lowering into the tokamak pit

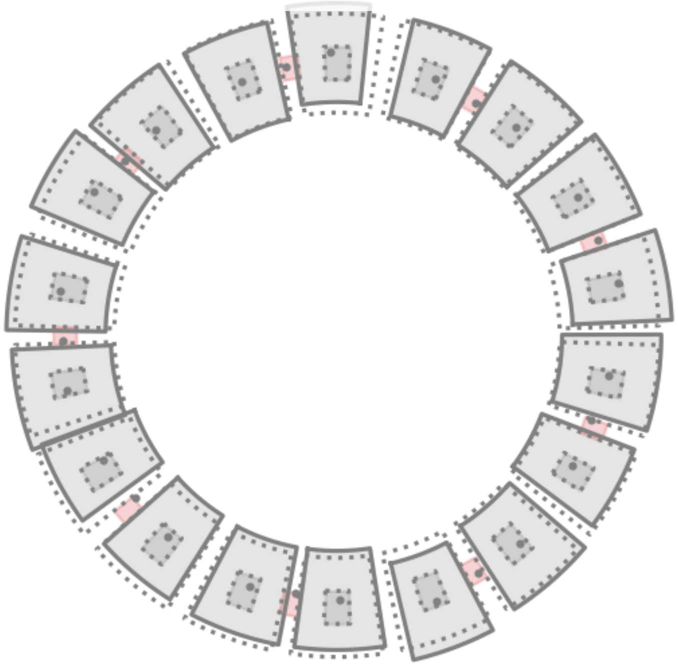
Alignment procedure completed



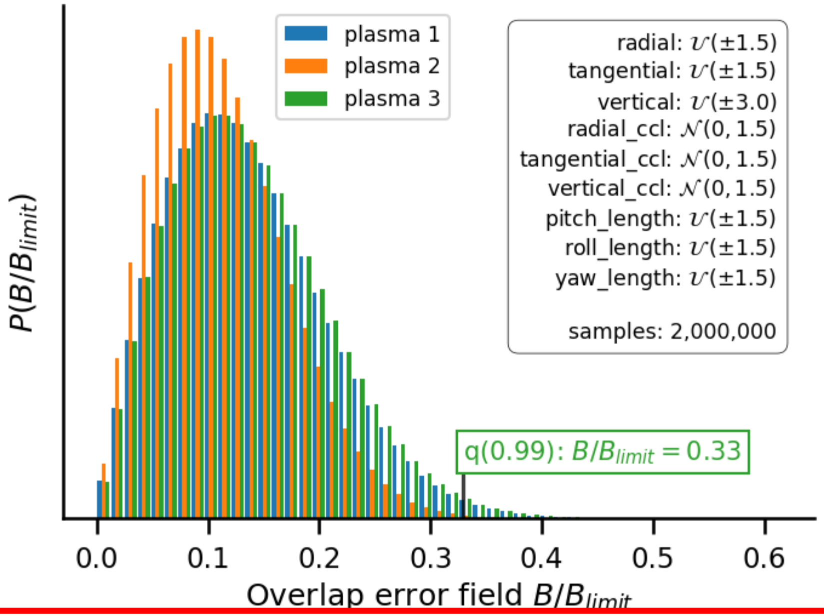


Alignment procedure guided by physics assessment of error fields

Alignment targets ensure that for 99% of the cases TF assembly will contribute less than 33% of the n = 1 overlap field (ITPA scaling)



(15 MA/5.3T : plasma 1 SOF, plasma 2 EOB)



TFC error field analysis will be extended to other coils and components

Issues found and solutions

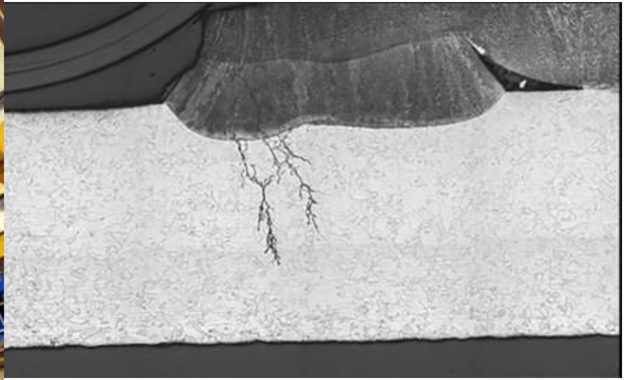
more details in

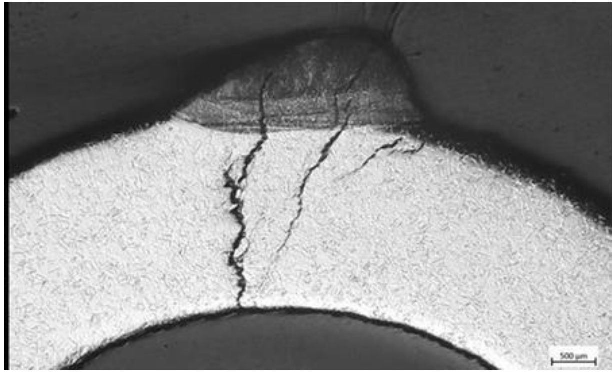
https://www.iter.org/newsline/-/3818

and

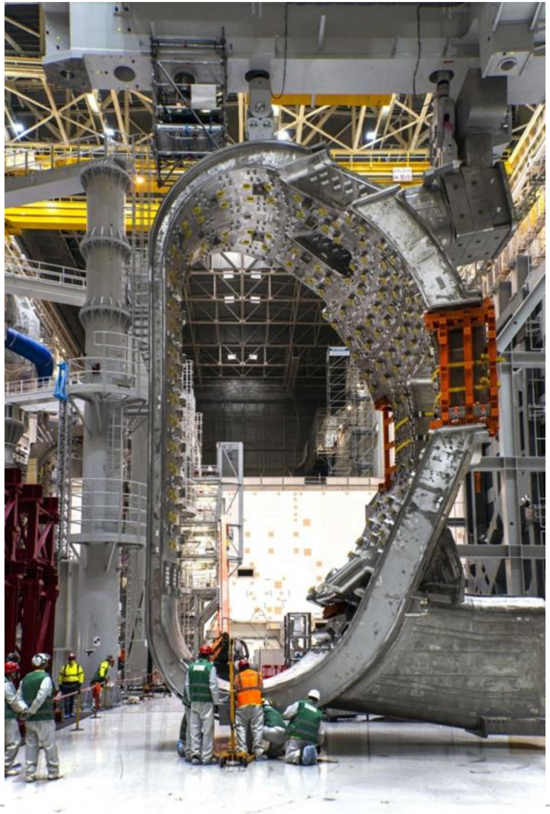
https://www.iter.org/newsline/-/3830

Corrosion of cooling pipes in thermal shields





Dimensional non-conformities of VV sectors impacting sector-to-sector welding



- **Solution for VV thermal shield → remove old pipes and re-weld new pipes (different steel and welding process/material) + re-manufacture of few panels → requires removal of installed shields from sectors**

- **Solution for Cryostat thermal shield → leave old pipes (unused) and re-weld new pipes (different steel/welding process/material) on-site**

- **Solution to VV non-conformity → remove and add material to meet required dimensions (73 - 400 kg per octant)**

Repairs to about to start (contracts will be signed soon) → duration of repairs cannot be precisely estimated at this time

ITER Research Plan (IRP) and burning plasma physics

ITER Research Plan (IRP)

IRP describes strategy for R&D to achieve Project goals starting from First Plasma to Q = 10 (300-500 s),Q = 5 (1000 s) & Q = 5 steady-state

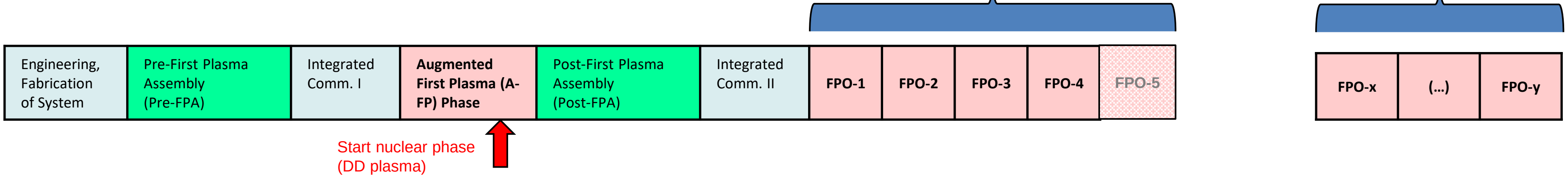
Proposed R&D is supported by available systems in each phase

- **Initial phase H (and D) to demonstrate :**
  - **15 MA/5.3 T plasmas in L-mode**
  - **Low/Medium current plasmas (I_p = 5 – 7.5 MA) in H-mode**
- **Main phase (D and DT) to demonstrate :**
  - **Burning Q = 10 plasmas**
  - **Long Pulse Q = 5 plasmas**

Details under reconsideration

ITER re-baselining

Proposed new baseline



Main features

- Pre First Plasma Assembly (Pre-FPA), most of in-vessel components installed (except water cooled Blanket First Wall)
- Augmented First Plasma Phase (A-FP) of about 2 years
- Post First Plasma Assembly (Post-FPA), complete installation of in-vessel components (incl. water cooled Blanket First Wall
- DT-1 operation stage of about 8-10 years to achieve Q = 10 within $3\ 10^{25}$ neutrons
- Second phase of ITER license
- DT-2 operation stage up to $3\ 10^{27}$ neutrons (Project Specification)

ITER re-baselining

Proposed baseline (Scenario B)

Engineering, Fabrication of System	Pre-First Plasma Assembly (Pre-FPA)	Integrated Comm. I	**Augmented First Plasma (A-FP) Phase**	Post-First Plasma Assembly (Post-FPA)	Integrated Comm. II	**FPO-1**	**FPO-2**	**FPO-3**	**FPO-4**	**FPO-5**

DT-1: FPO-1 to FPO-5

DT-2: **FPO-x** | **(…)** | **FPO-y**

Start nuclear phase (DD plasma)

Objectives:

- To develop plasma scenarios (incl. start-up, ramp-up, flat-top and ramp-down);
- To test the Plasma Control System;
- **To commission the Disruption Mitigation System**;
- **To achieve DD plasma operation in H-mode**
- **To demonstrate L-mode operation to high I_p (15 MA)**

Constraints:

- Divertor fully installed and actively cooled **but Blanket Shield Blocks not actively cooled and protected by radiative W tiles**
- Max neutron budget to enable person access inside the VV for post-First Plasma installations

Objectives:

- To develop DD-similar scenarios for the inductive (15 MA), long pulse (12.5 MA) and steady-state (10 MA) high Q scenarios to be demonstrated later in DT;
- To demonstrate routine plasma operation with low disruptivity in the DD-similar high Q scenarios;
- To assess impact of T (from trace level to ~ 10-20%) on plasma behaviour in the DD-similar high Q scenarios
- To demonstrate Q = 10 operation for 300-500 s in DT plasmas with 15 MA/5.3 T
- To implement the TBM Program

Assumption:

- Blanket First Wall with tungsten armour

Constraints:

- Max neutron budget to enable SDDR within acceptable limits with the present conservative assumptions and avoid the production of type B radwaste

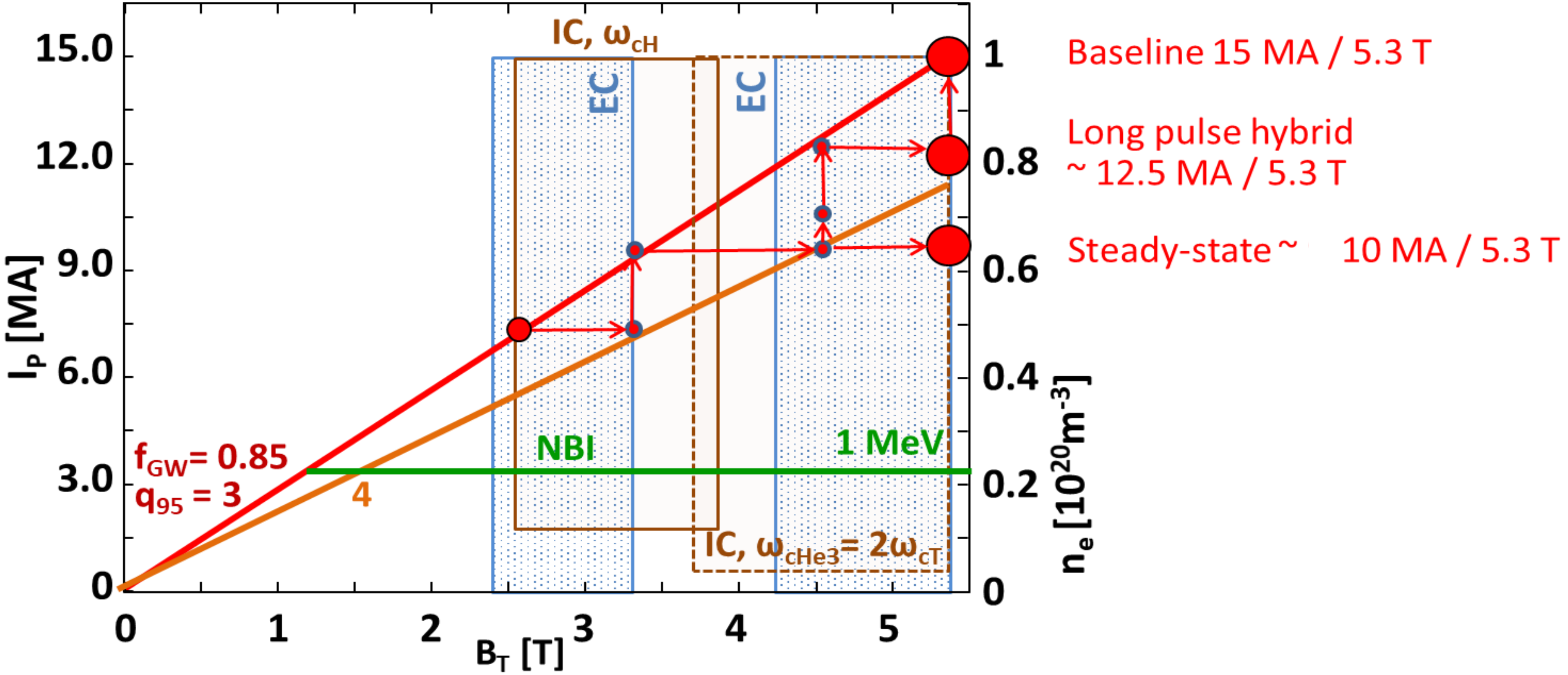
Objectives:

- To demonstrate Q = 5 long pulse operation (1000 s) in DT plasmas with 12.5 MA/5.3 T;
- To demonstrate Q = 5 steady-state operation (3000 s) in DT plasmas wit 10 MA/5.3 T;
- To demonstrate high-duty routine plasma operation in the Q = 10 and the two Q = 5 scenarios for fusion technology demonstration and tests (T-breeding with TBM, system operational reliability, etc.)
- To assess DEMO issues such as power exhaust solutions, optimization of T fueling and processing, etc.

Constraints:

- Target neutron budget as per Project Specification depending on outcome from DT-1 and machine upgrade capabilities

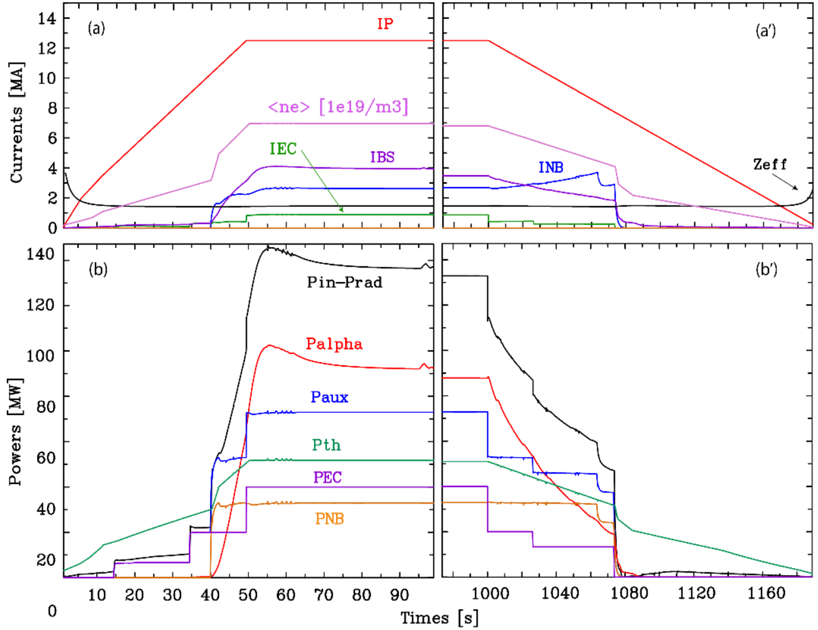
Fusion Power Operation (D/DT)



ITER burning plasma scenarios

ITER Q ≥ 5 scenario (1000s burn)

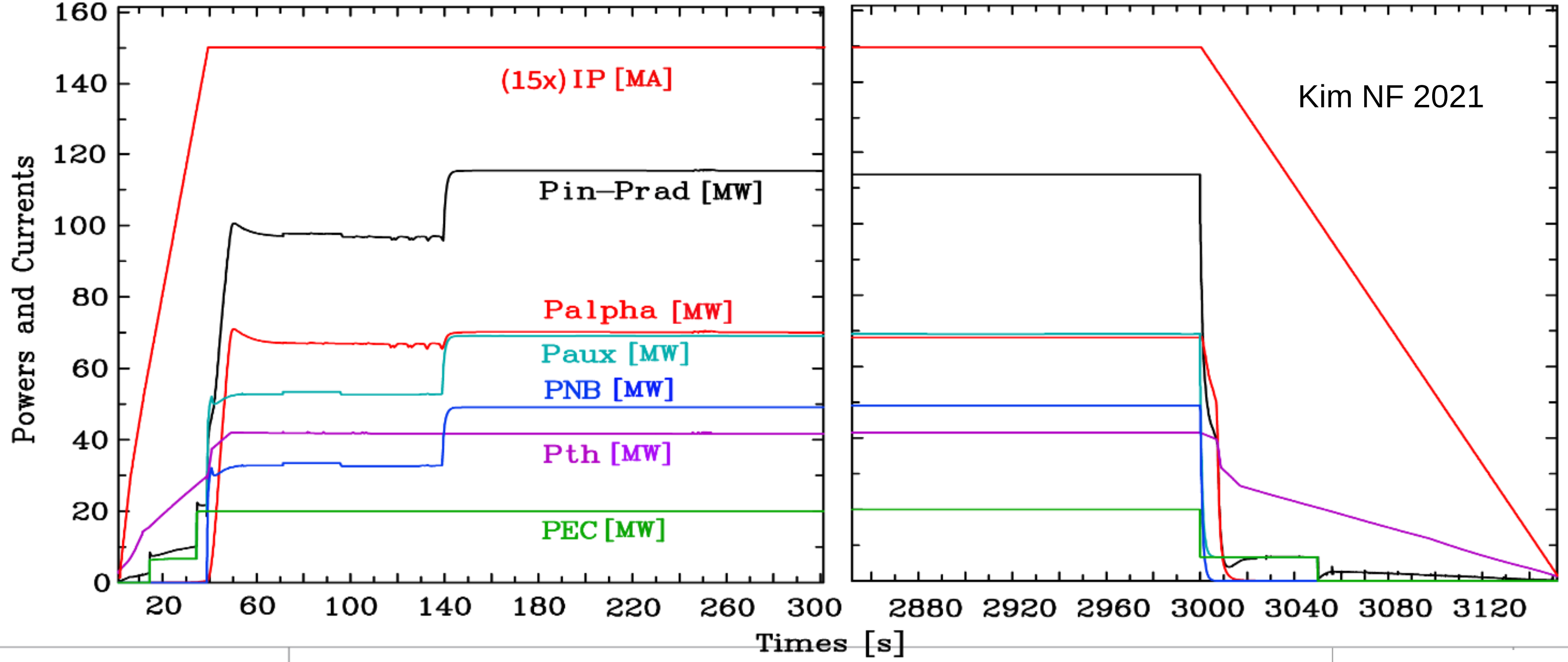
- Main option is based on improved H-mode/hybrid scenario with q(0) > 1 and H_{98} > 1.2 with burn length limited by q(0) reaching 1 (12.5 MA/5.3 T)
- Obtained with $P_{aux} = P_{NBI} + P_{ECH}$ (+ P_{ICH}) ≥ 50 MW with non-inductively driven current ~ 55%



S.H. Kim

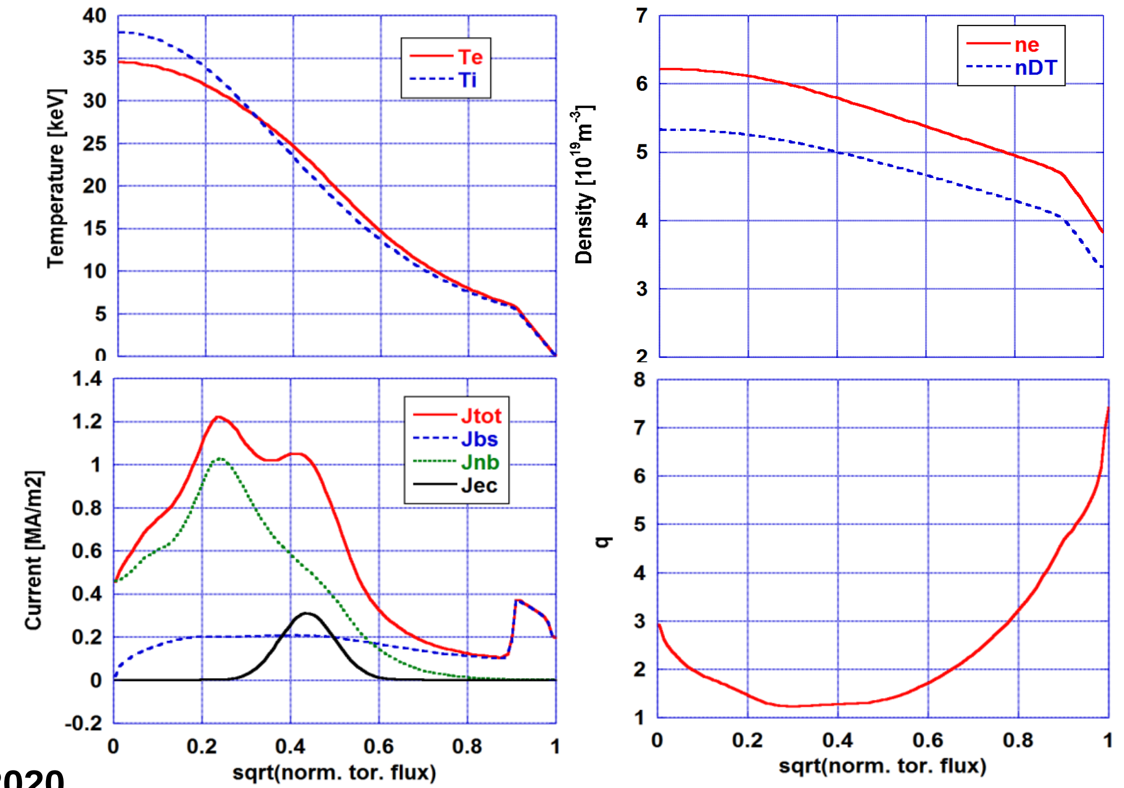
ITER Q ~ 5 scenario (steady-state)

- Based on improved H-mode/hybrid scenario with stationary q profile (q > 1) and H_{98} > 1.5 length limited to 3000s by hardware design (10 MA/5.3 T)
- Obtained with $P_{aux} = P_{NBI} + P_{ECH} \geq 70$ MW with non-inductively driven current ~ 100%



Q = 5 steady steady-state plasma at 10 MA

- **Conditions identified by 1.5-D ASTRA modelling**
  - ✓ EPED1+SOLPS used for pedestal and boundary
  - $Q=5.02$, $f_{GW}=0.69$
  - $H_{98}=1.52$, $\beta_N=3.02$
  - $q_{min}=1.23$
  - Relatively high $l_i(3)\sim0.87$ mainly due to 50 MW NBI (+ 20-30 MW ECH)
  - Improved confinement is essential



Polevoi – NF 2020

Energetic ions in ITER scenarios - I

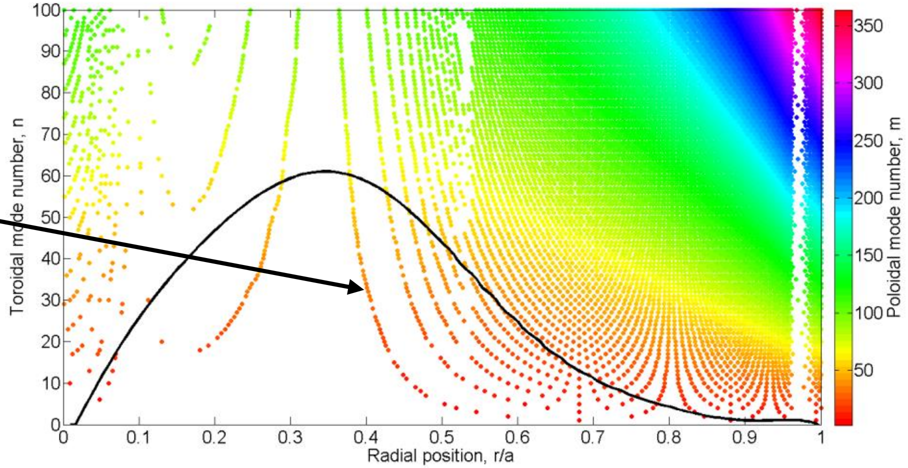
- Energetic ions impact on ITER burning plasmas
  - Can drive MHD Alfvén eigenmodes → energetic ion loss $P_\alpha \downarrow$ ☹
  - Can reduce anomalous transport level → higher τ_E → $P_\alpha \uparrow$ ☺
  - Can increase core plasma β and thus shafranov shift → increased edge stability/pressure → increased τ_E → P_α ☺
  - Alfvén eigenmodes can reduce plasma turbulence → higher τ_E but energetic ion loss → P_α ? ☺
- Coupling between all effects difficult to predict in quantitative way for ITER burning plasmas since P_α is dominant

Energetic ions in ITER scenarios - II

- **Consequences of EP-driven Alfvén eigenmodes range from**
  - **Benign saturation → significant high-amplitude bursting and transport**
- **Extrapolation from present machines difficult due to small** $\rho_\alpha / a \simeq 10^{-2}$

- **Besides loss of heating, ITER first wall loads acceptable for fast ion losses of a few %**
- **Max power transfer from α's occurs when drift orbit width ~ mode width → n ~ 30**
- **Many overlapping AE**

Radial localisation of TAE gaps in ITER Q = 10 plasmas

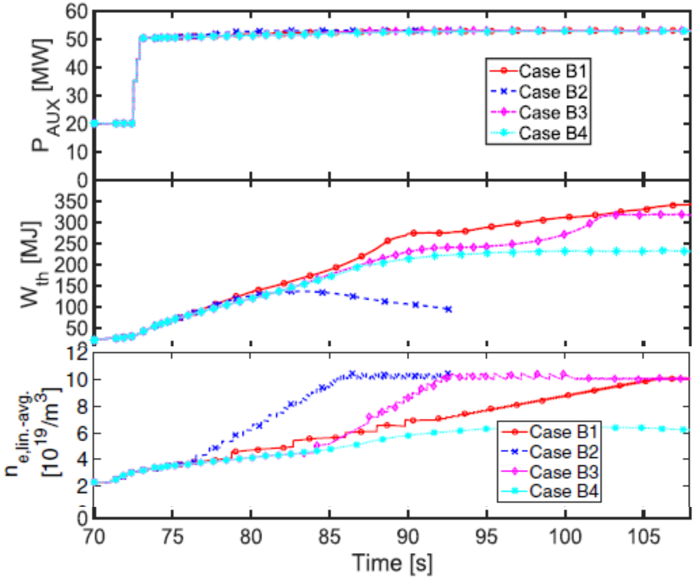


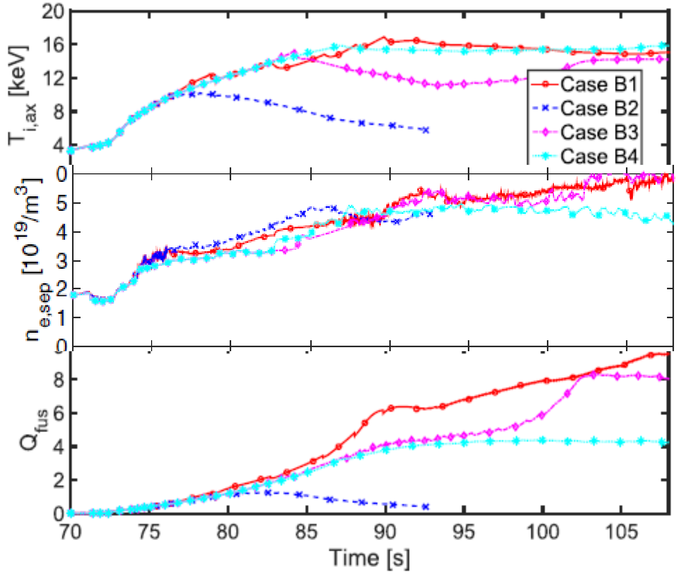
ITER will quantify impact of fast ion instabilities in Q = 10 plasmas and explore means for mitigation and control

Access to high Q conditions

- Access to high Q requires build-up of P_α since P_{aux} is moderate and P_{L-H} is high
- Key to high Q access is density control (gas fuelling for n_{sep} and pellet fuelling for n_{core})

F. Koechl - ITER – JINTRAC - NF 2020





Conclusions

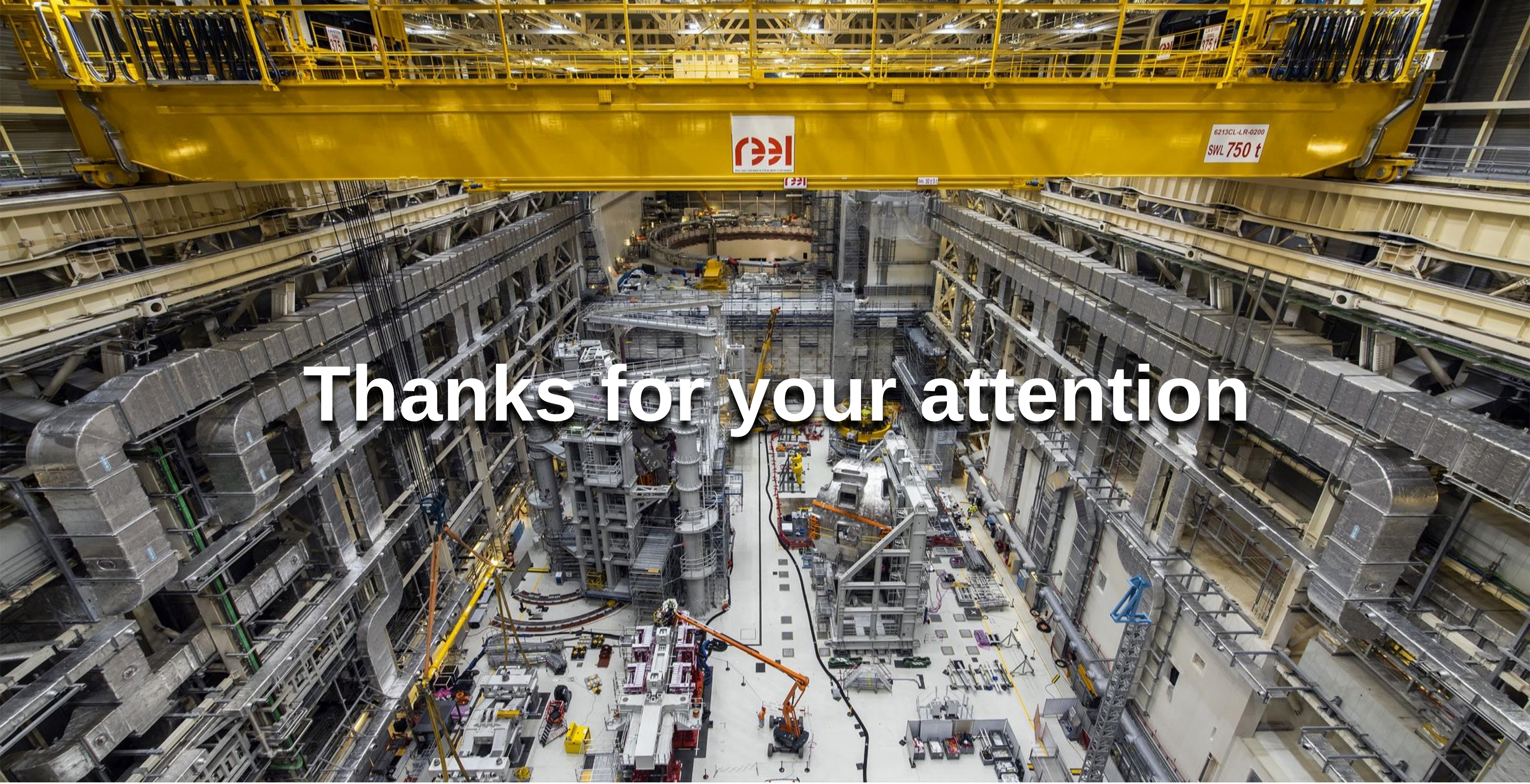
- ITER will demonstrate the scientific and technological feasibility of fusion power as energy source for humankind
- ITER construction is progressing despite challenges → commitment from ITER Organization and its Members
- ITER Research Plan provides experimental strategy to progress from First Plasma through to achievement of Project's goals: Q = 10 (300-500 s), Q = 5 (1000 s) & Q = 5 steady-state
- ITER high Q scenarios will address key burning plasma issues for reactors:

✓ Coupling of physics processes in self-heated plasmas

✓ Integration of core-edge physics to achieve burning plasma conditions with acceptable edge plasma conditions

✓ Effectiveness of actuators and control schemes for burning plasmas → high Q disruption-free operation

✓ In addition many fusion reactor technologies will be demonstrated (Tritium cycle, TBMs, H&CD, PFCs, etc.)



Thanks for your attention