Objectives and status of the ITER Project

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Science, Controls, and Operation Department
ITER Organization

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

Outline of talk

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

Personal Journey

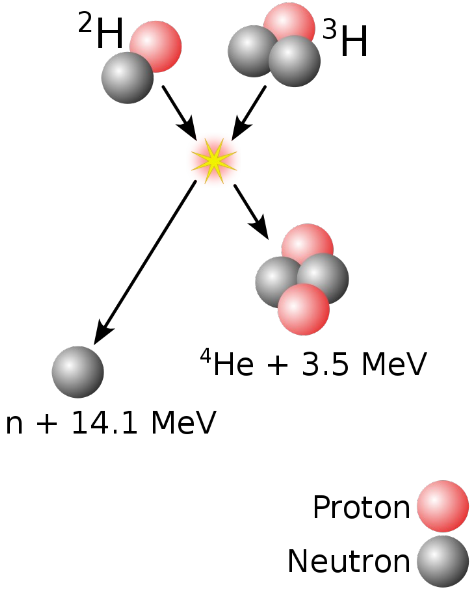
- Bachelor in Theoretical Physics (interested in Astrophysics) at UCM – Madrid
- PhD in fusion plasma theory at UCM → short stay at JET (2 → 6 months)
- Change of PhD topic : edge plasma experiments and modelling at JET
- Postdoc at JET 2-D edge modelling and experiment (detachment) → participation in ITER expert groups (International Tokamak Physics Activities)
- Move to ITER EU Home Team (IPP-Garching) → R&D for ITER (exp. + modelling - ELMs R&D), EU R&D PWI programme management, ITPA DivSOL
- Move to ITER Organization → Science, Controls and Operation Department
    - Edge/Pedestal physics and Edge-core plasma integration, Science and Technology Advisory Committee Secretary, ITPA Edge and Pedestal
    - Section Leader Confinement & Modelling, STAC Secretary, ITPA Transport & Conf.
    - Science Division Head :
      ITER Research Plan, Plasma Control System design, Integrated Modeling and Analysis Suite

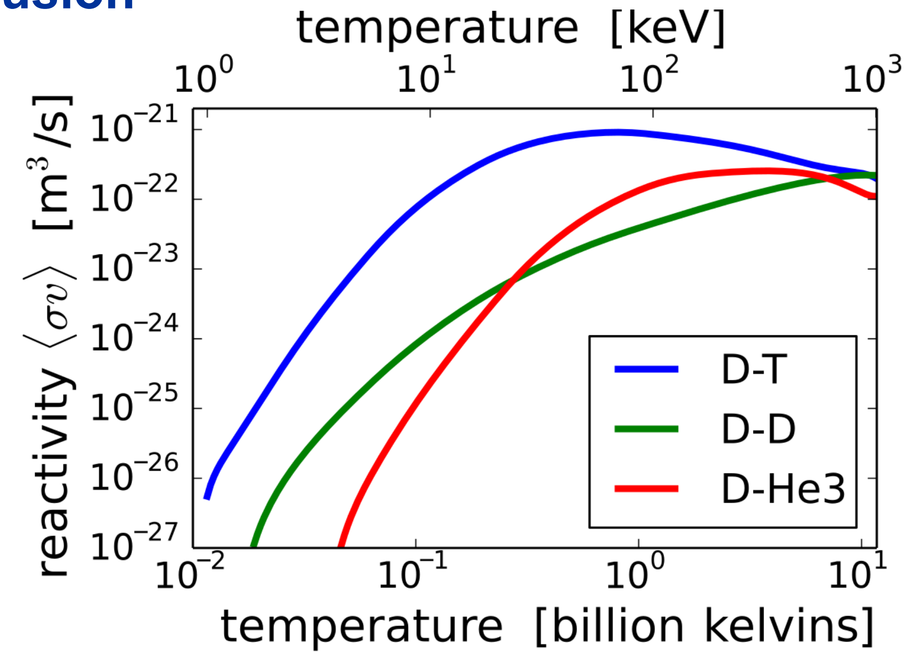
ITER Mission, Basis, Goals and overall design

ITER Mission

To demonstrate the scientific and technological feasibility of fusion power as energy source for humankind

D (^{2}H) + T(^{3}H) fusion





ITER Basis: DT Fusion Power Production

- **Net production of fusion energy**

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

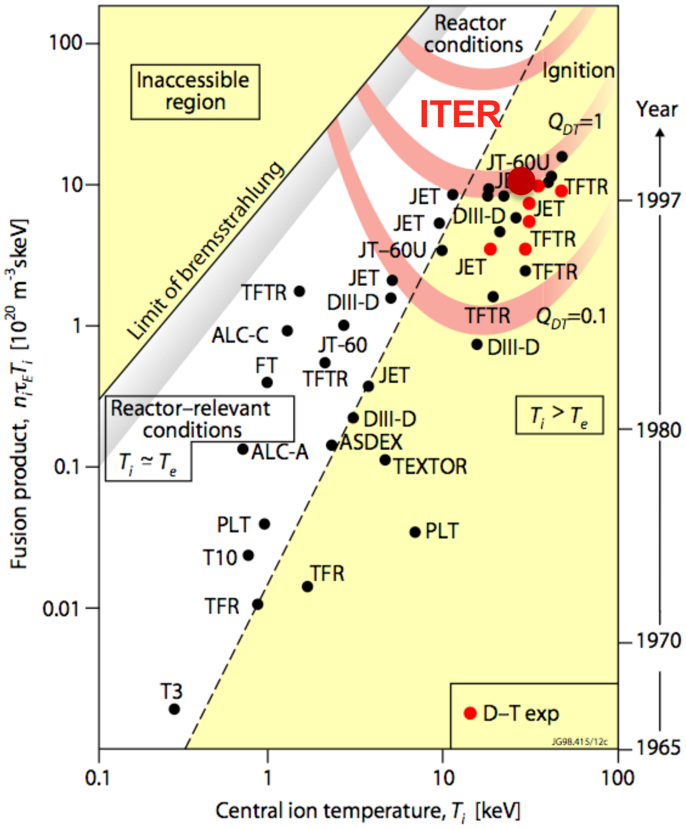
$$Q = P_{fusion}\ (^4He + n)/P_{external\text{-}heat}$$

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

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

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

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

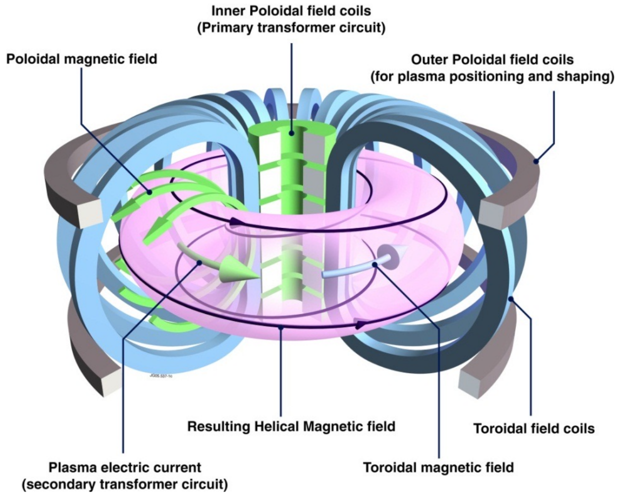


ITER Basis: Magnetic Confinement

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**



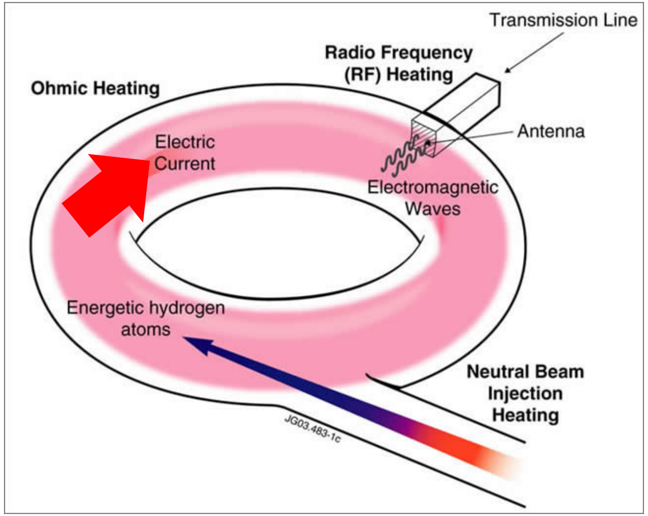
Tokamak

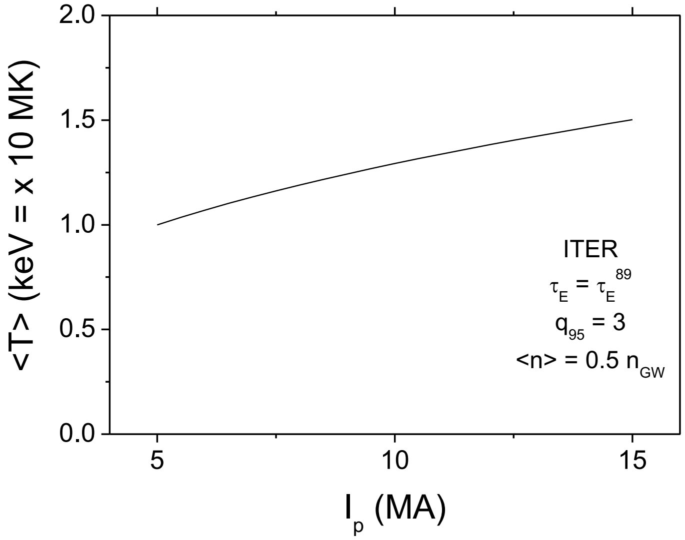
$$q = \frac{Toroidal\ turns}{Poloidal\ turns} \geq 2$$

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**

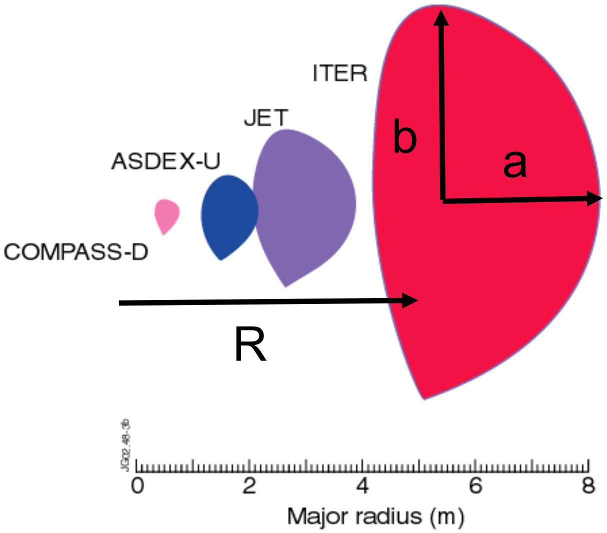




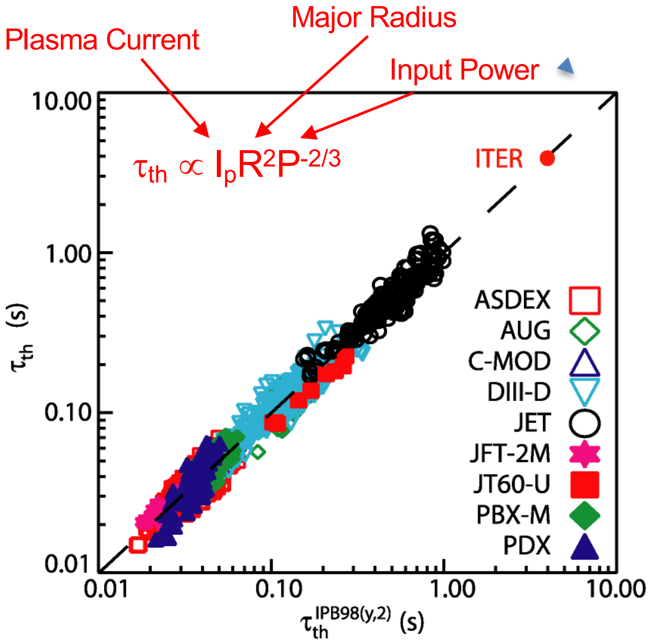
ITER Basis: Energy Confinement (τ_E)

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

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



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



$$q_{95} = 3$$

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

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:**

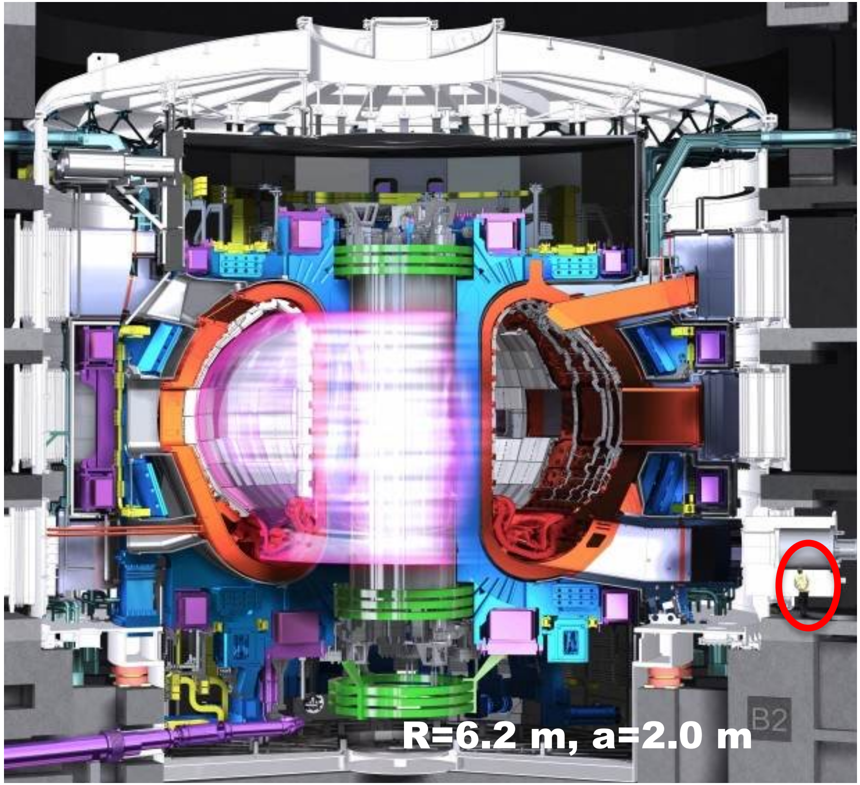
Q ~ 5 for long pulses up to 1000 s

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

- **Steady-state operation:**

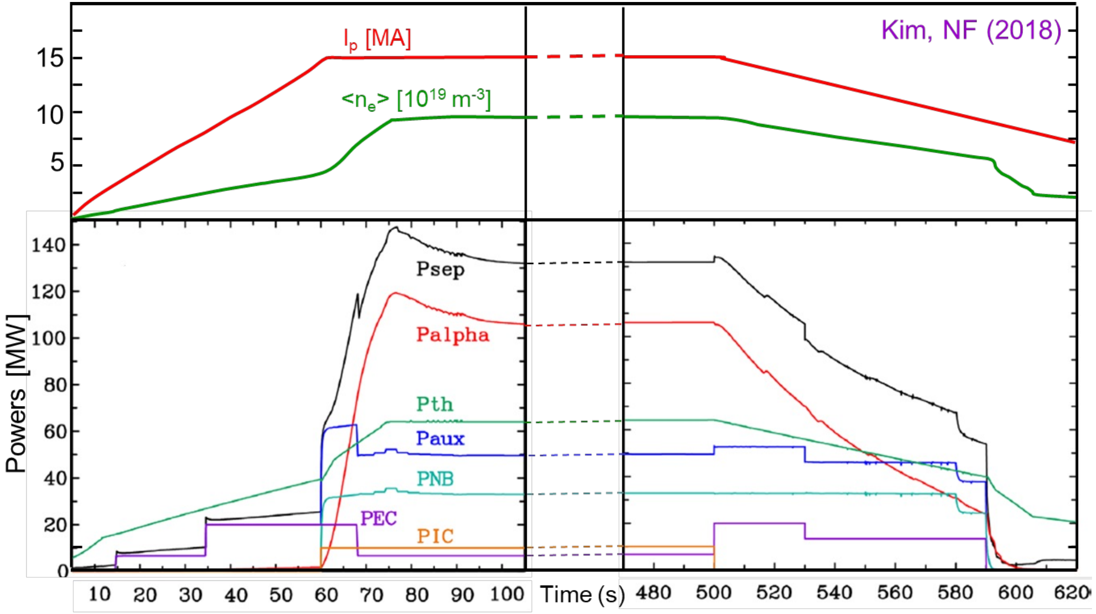
Q ~ 5 for long pulses up to 3000 s, with fully non-inductive current drive

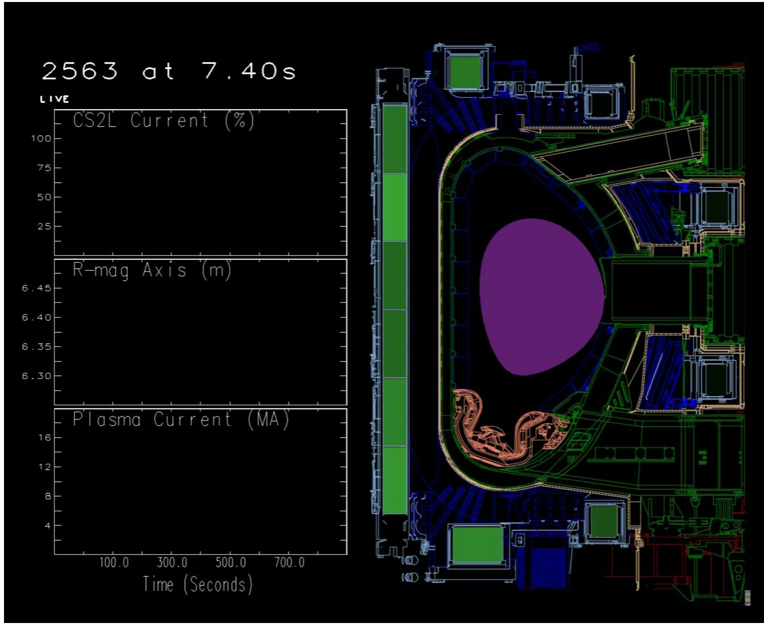
→ **Steady-state scenario ~ 10 MA / 5.3 T**



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%

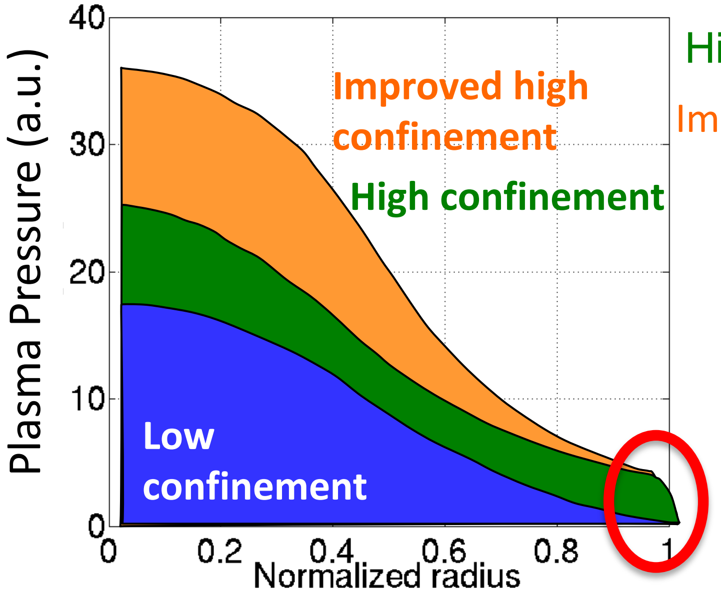




Few key ingredients to achieve ITER's fusion goals - I

❑ Achievement of high energy confinement plasmas

$P_{fusion} \sim W_{plasma\text{-}th}^2$



Low confinement (L-mode): pulsed operation ($H \sim 0.5$)

High confinement (H-mode): pulsed operation ($H \sim 1$)

Improved high confinement: long pulse ($H \sim 1.2$) / steady-state ($H \sim 1.6$)

Power threshold for transition from L to H-mode:

$$P_{L-H} \propto n_e^{0.7} \times B^{0.8}$$

(empirical basis)

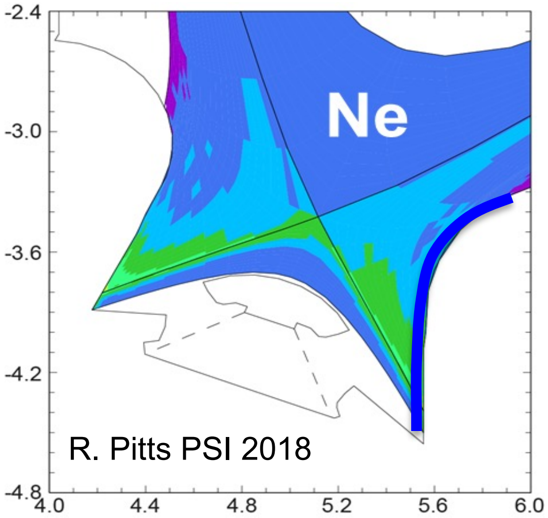
$$P_{L-H}(\boldsymbol{T}) < P_{L-H}(\boldsymbol{D}) < P_{L-H}(\boldsymbol{H})$$

$$P_{L-H}(\boldsymbol{He}) \sim P_{L-H}(\boldsymbol{H}) / 1.5$$

Few key ingredients to achieve ITER's fusion goals - II

❑ Edge-core integration : stationary and ELM transient power fluxes

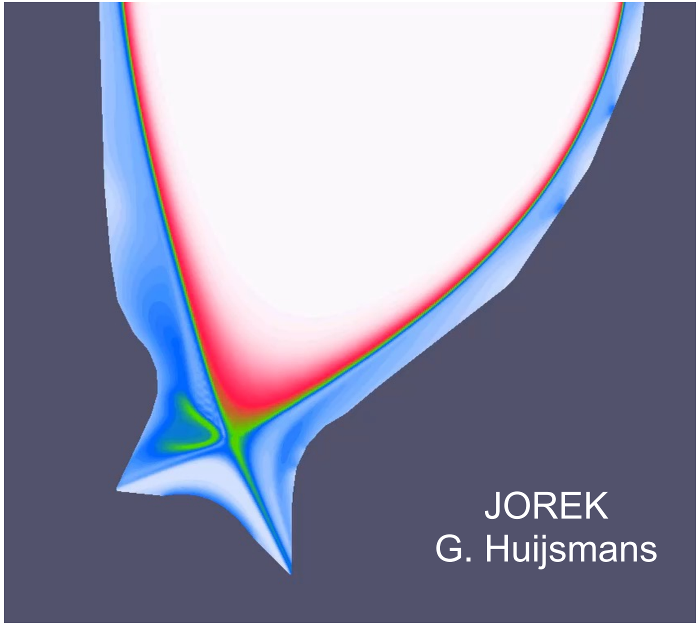
Radiative Dissipation



$P_{RAD,DIV}$ = 56.6 MW

q_{div} < 10 MWm^{-2}

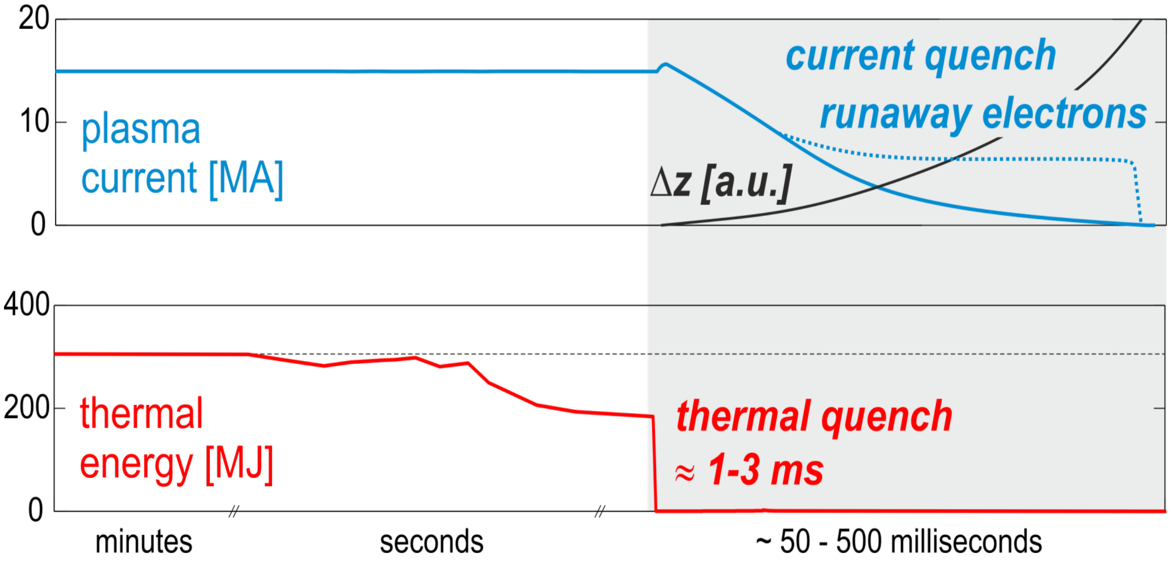
ELM control : Mitigation by f_{ELM} increase and suppression

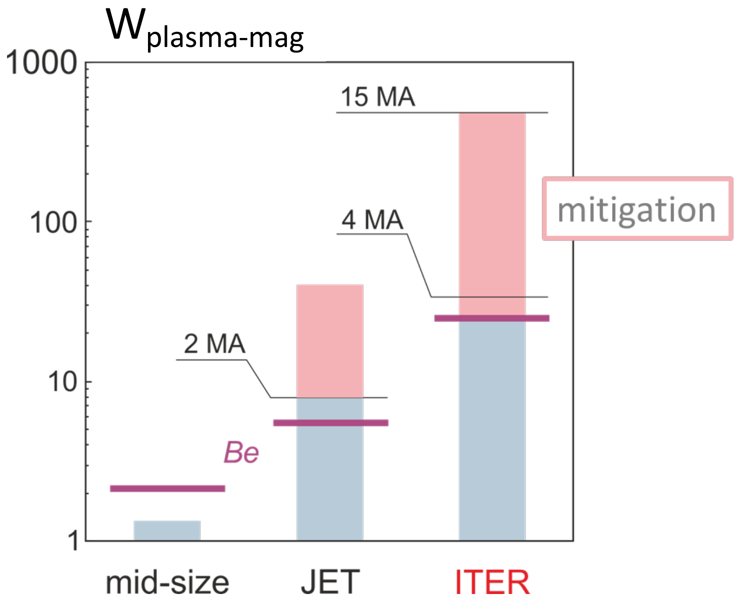


Few key ingredients to achieve ITER's fusion goals - III

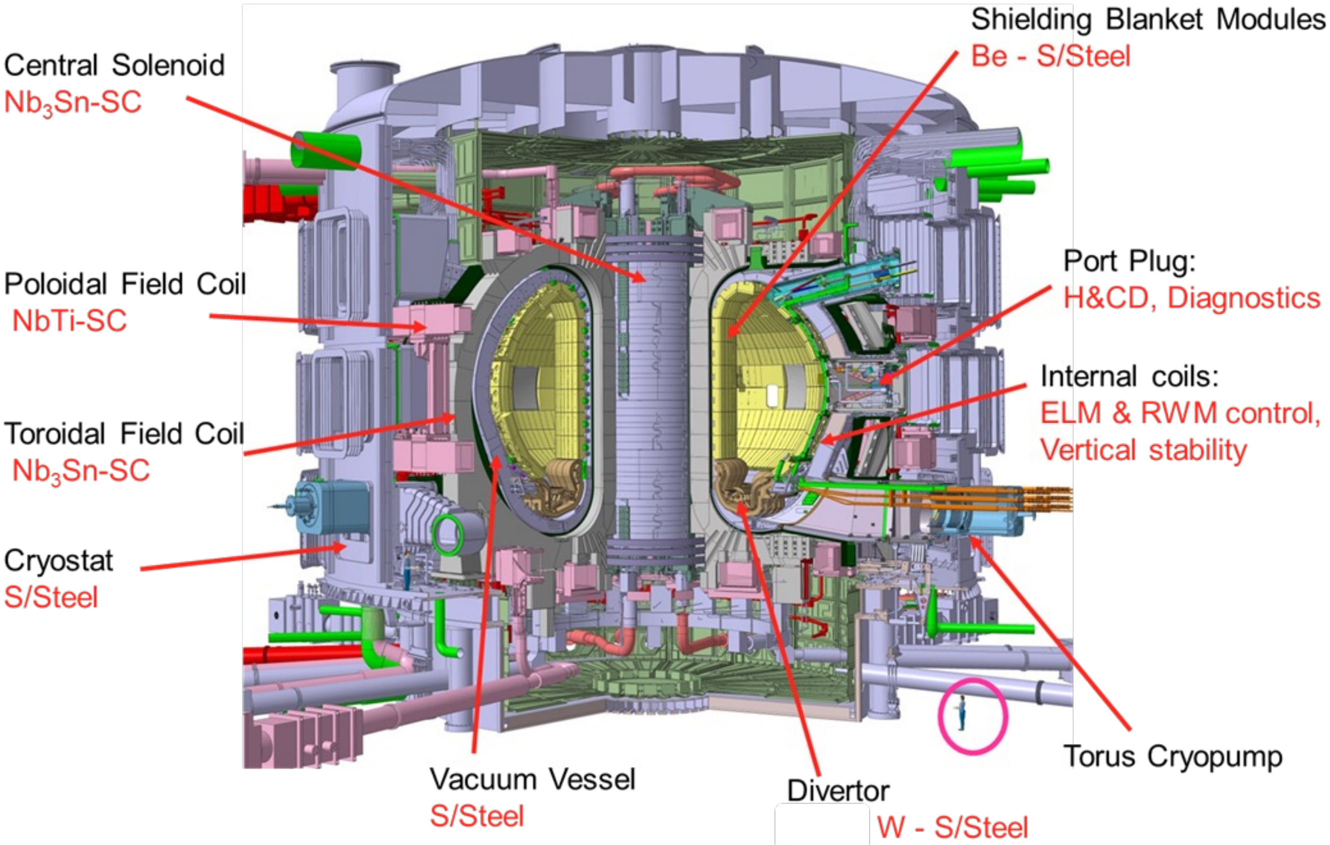
- ❑ **MHD stable plasma operation + mitigation if global instabilities develop (disruptions)**

M. Lehnen EPS 2017

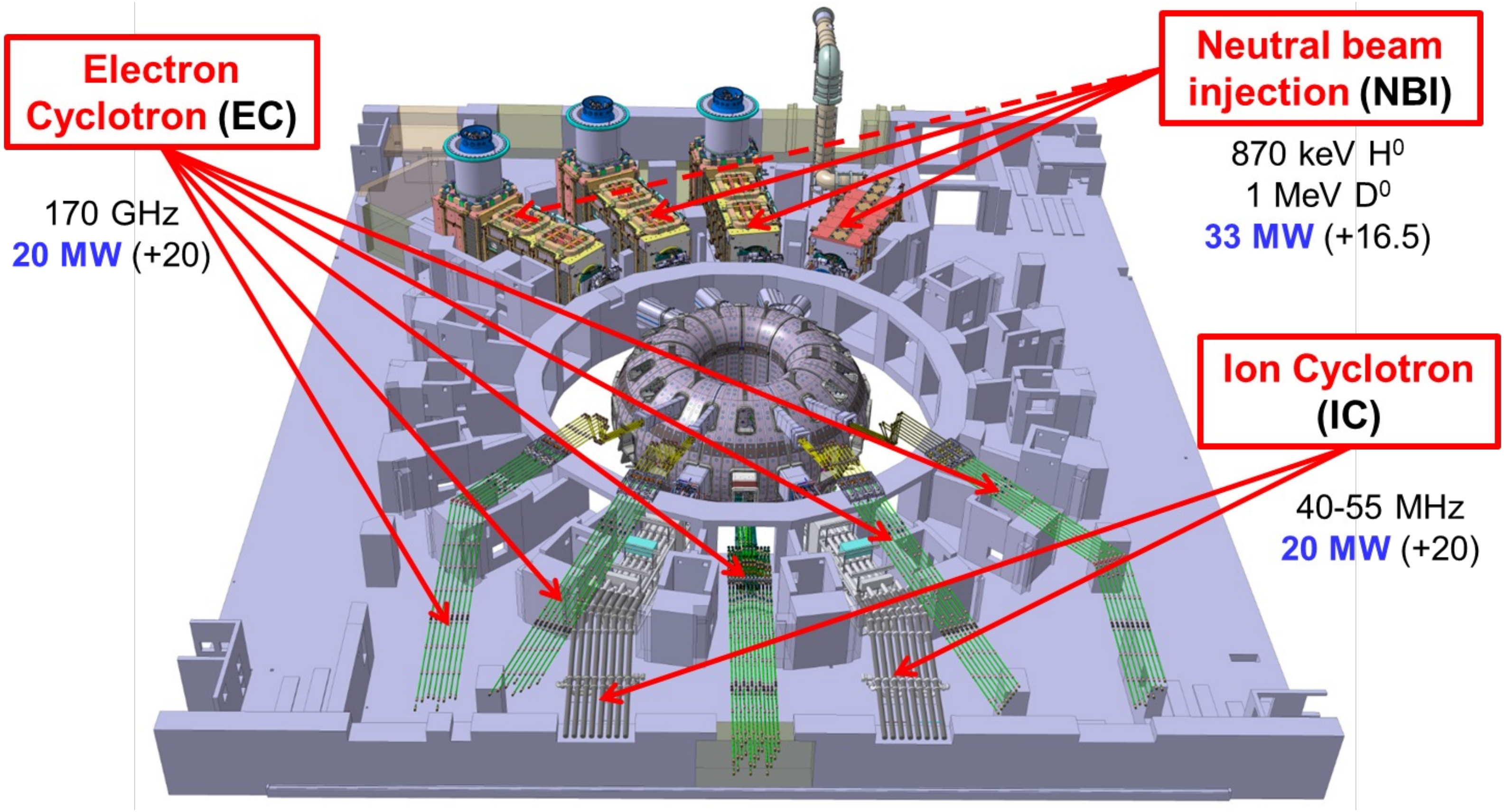




ITER Main Design Features

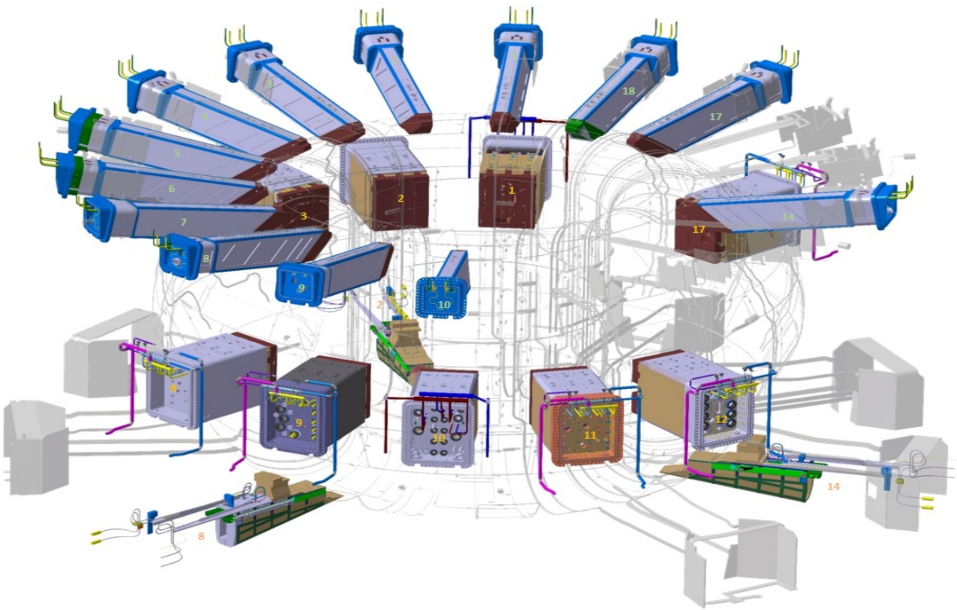


ITER Heating and Current Drive systems

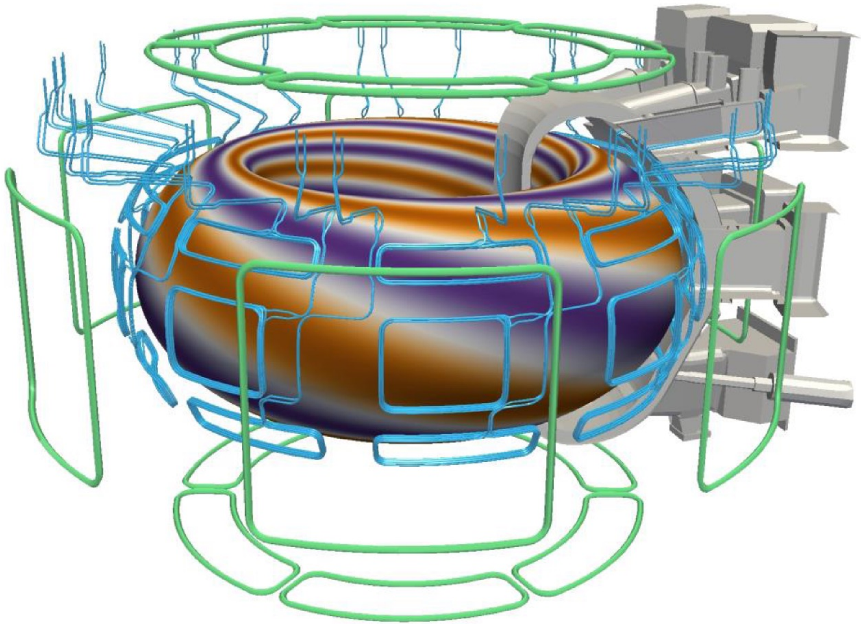


ITER Diagnostics and 3-D coils (Error Field, ELM control)

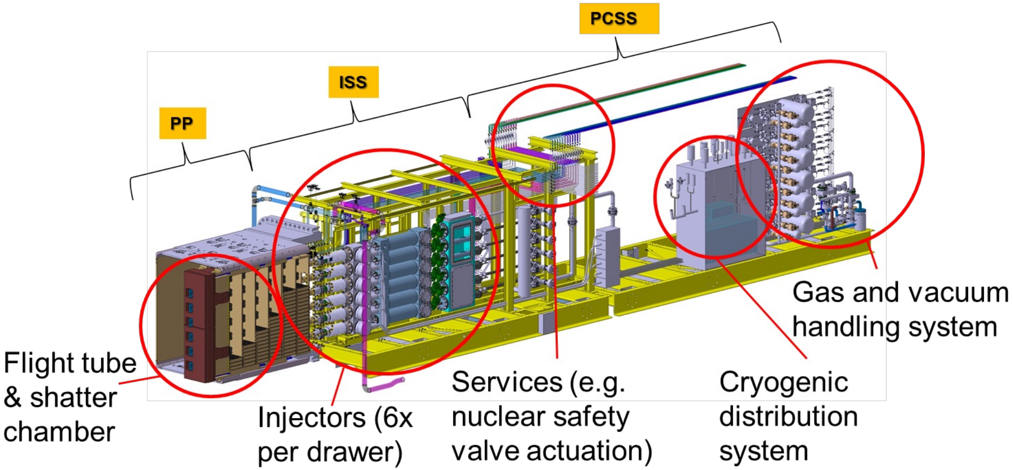
- ❑ Diagnostics: ~ 60 instruments measuring ~ 100 parameters

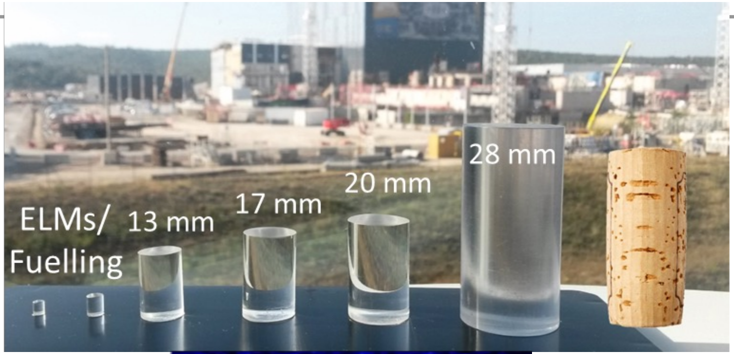


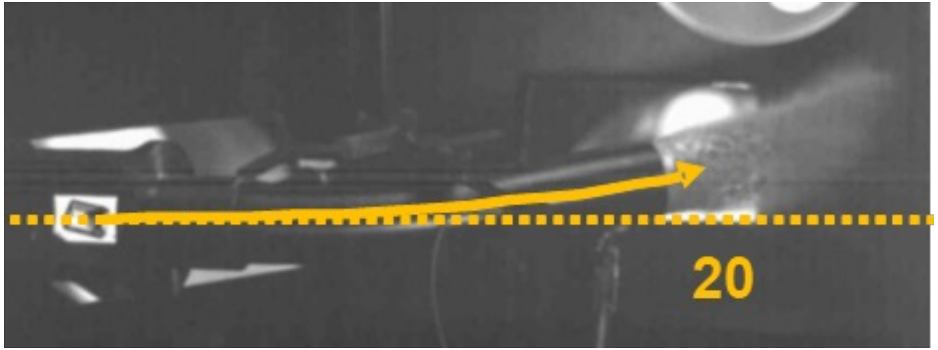
- ❑ External error field correction coils + internal ELM control coils

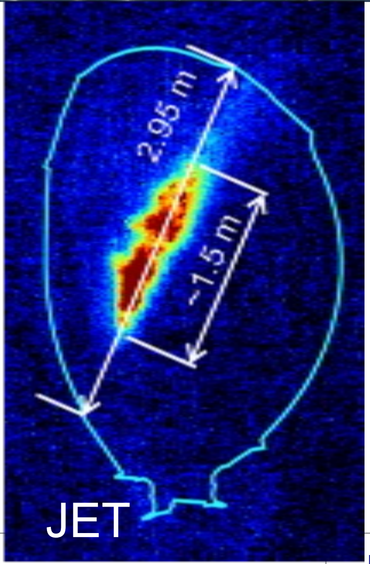


ITER Disruption Mitigation System







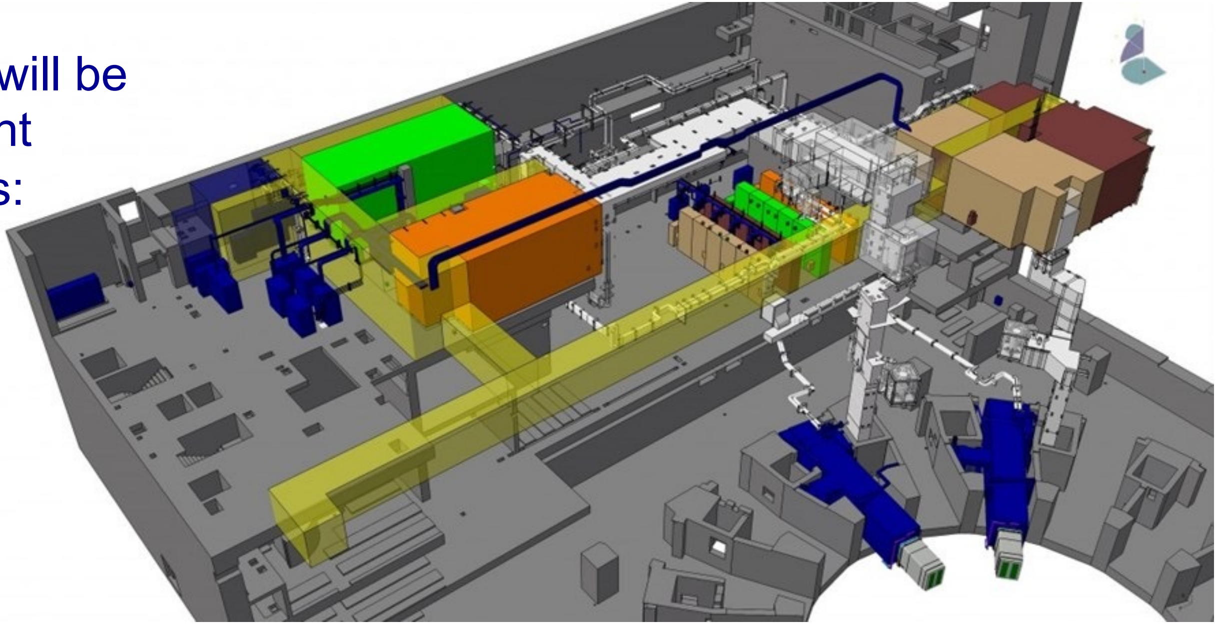


Tritium Breeding : Test Blanket Systems

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

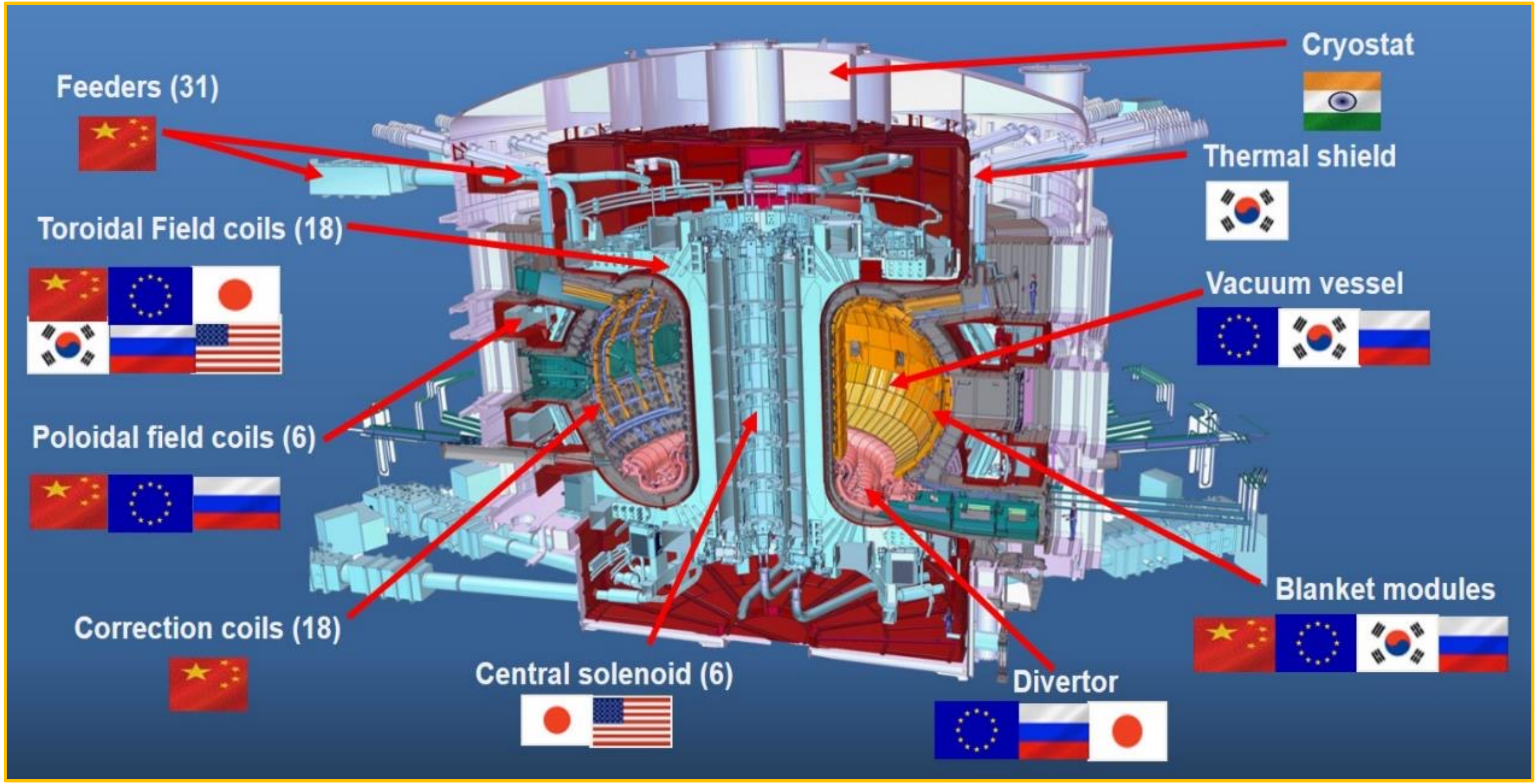
Global challenge, global response

- 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.

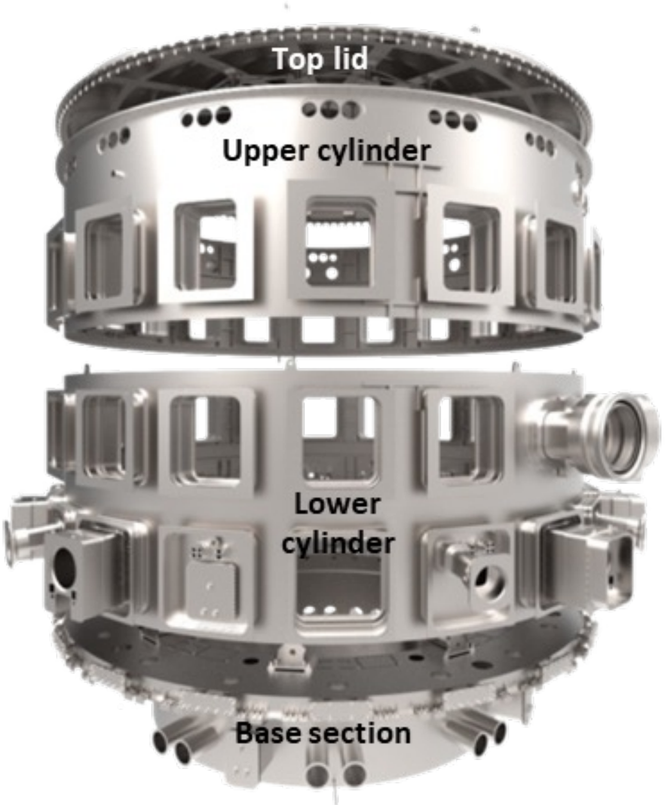
The seven ITER Members represent more than 50% of the world's population and about 85% of the global GDP

China EU India Japan Korea Russia USA

Construction ITER – Who manufactures What ?



ITER Cryostat

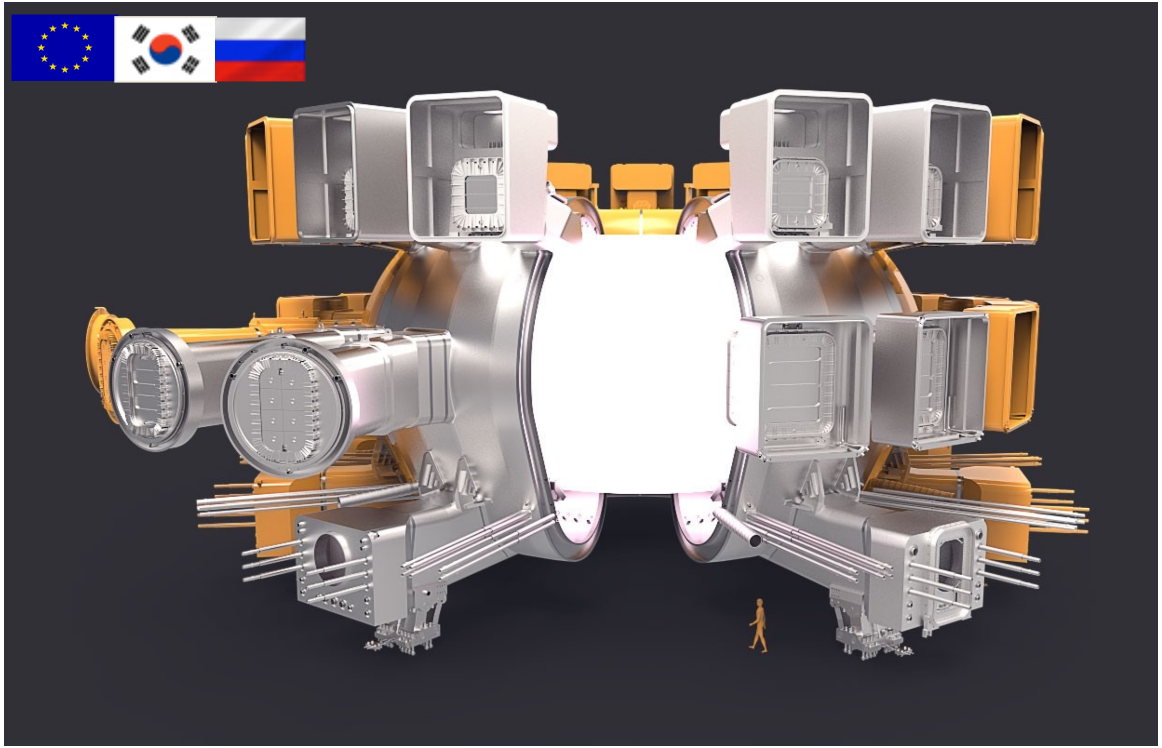


Largest stainless steel high-vacuum pressure container ever built

Provides high-vacuum and ultra-cool environment

Height: 30 m
Diameter: 30 m
Weight: 3,850 t

ITER Vacuum Vessel



Double wall steel container

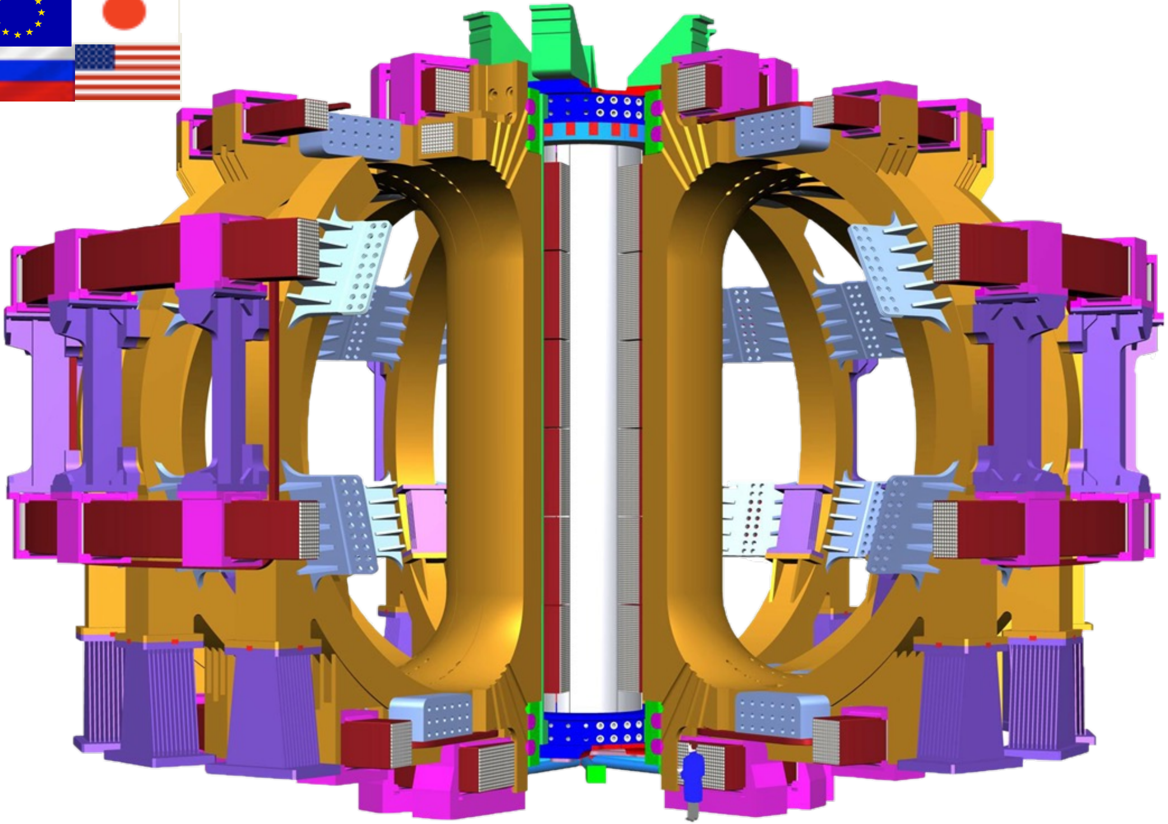
- blanket modules
- cooling water

High-vacuum environment

Primary containment barrier

Volume: 1,400 m^3
Plasma volume: 840 m^3
Weight: 8,500 t

ITER Magnet System

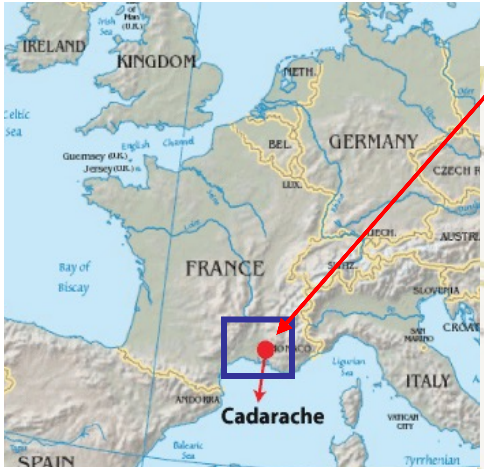


Central solenoid
- 13 m high
- 1,000 tons

18 toroidal field coils
- 17 m high
- 360 tons each

6 poloidal field coils
- 8-24 m in diameter
- 200-400 tons

Itinerary of ITER Components



ITER Site

= Itinerary of ITER Components

Many massive arrivals in 2020-23 (few shown)

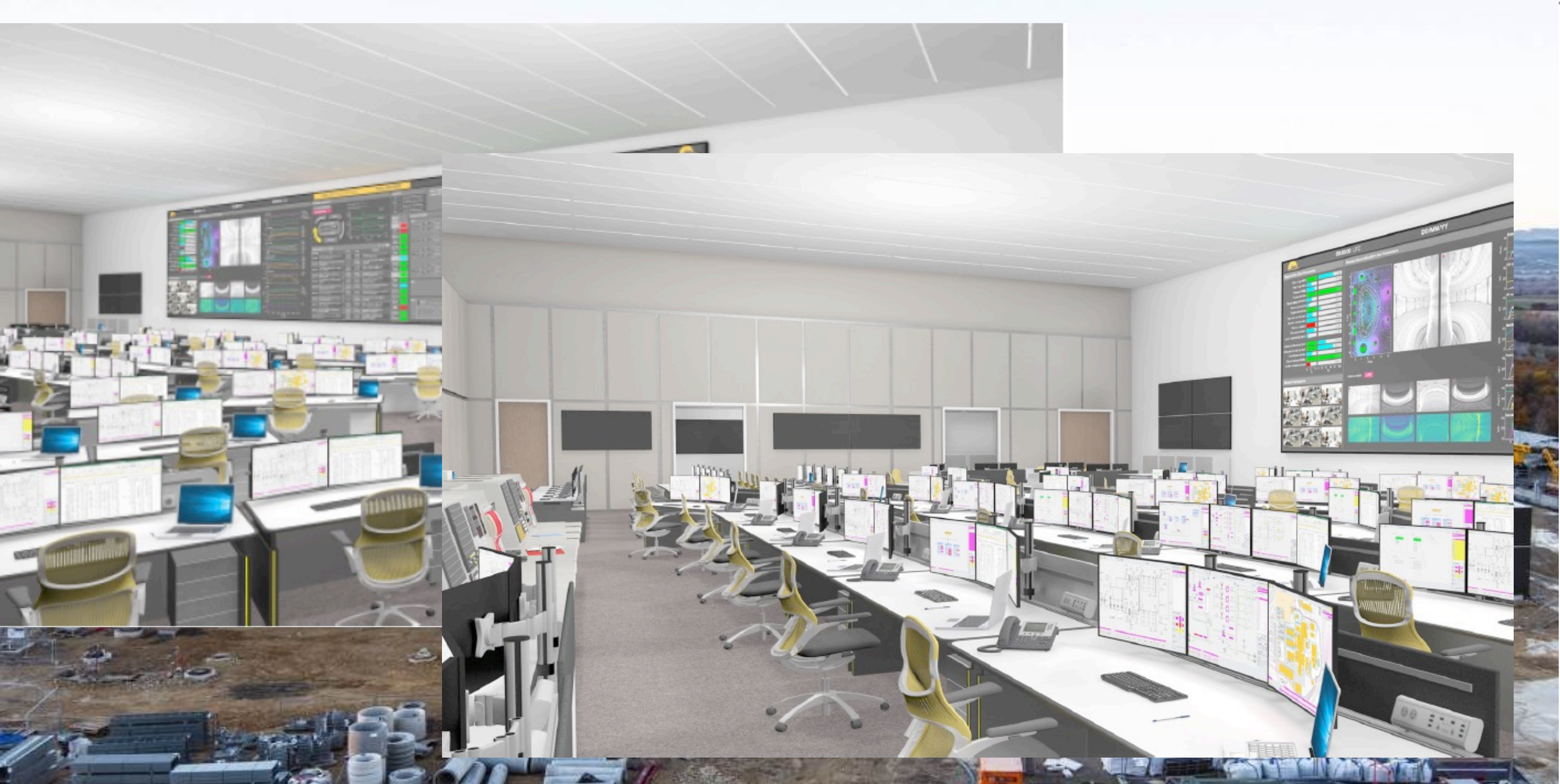
ITER Site Construction Status

ITER construction site drone view

March 2023

Worksite progress

ITER Control Room



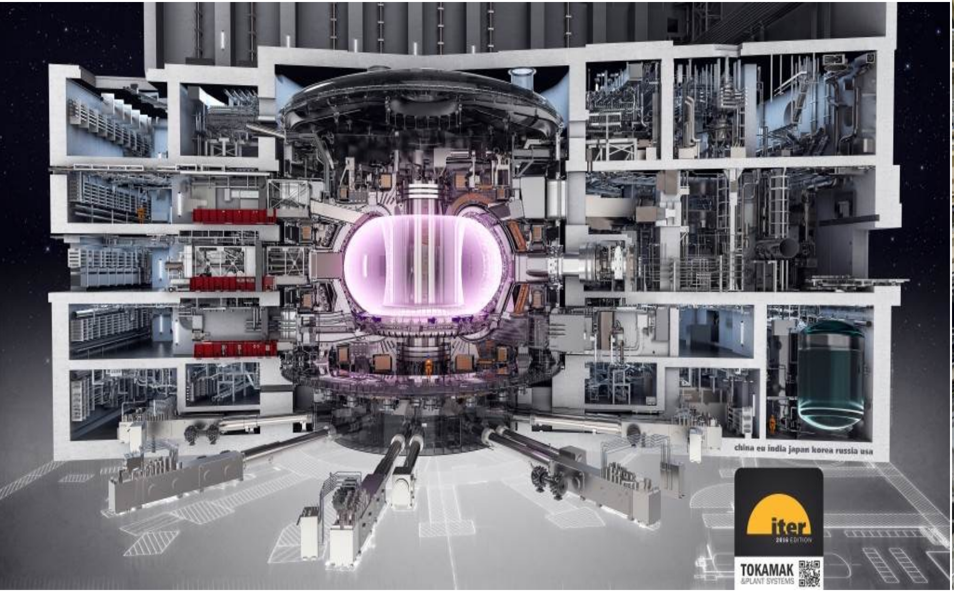
Balance of plant
Towards commissioning

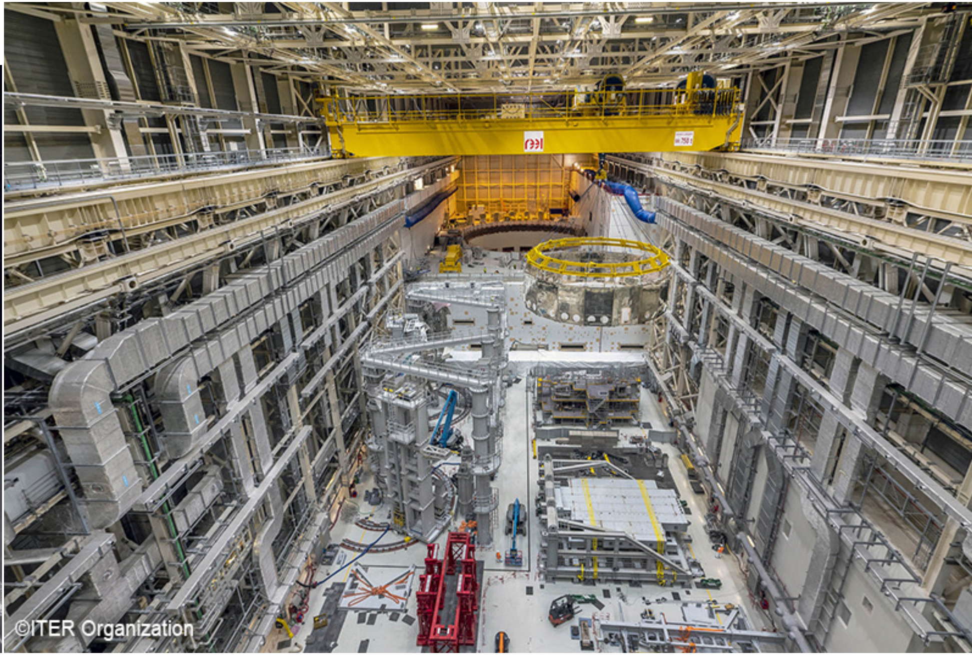
Cryoplant:
5 000 tonnes of equipment
LHe: 25 t
Cooling Power:
75 kW at 4.5 K (Helium)
1300kW at 80 K (Nitrogen)

ITER Tokamak Assembly Status

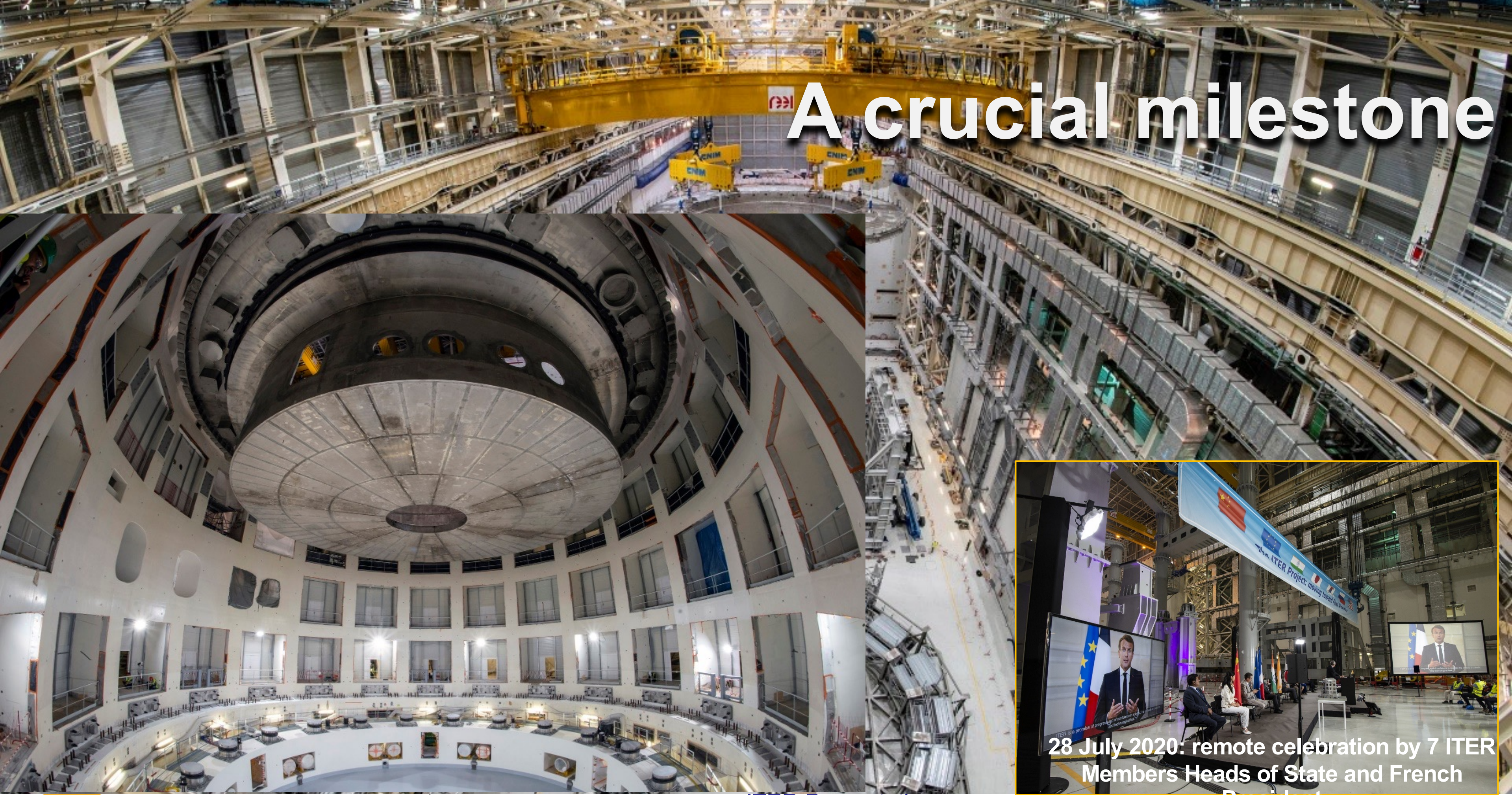
Assembly Hall and Tokamak building

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





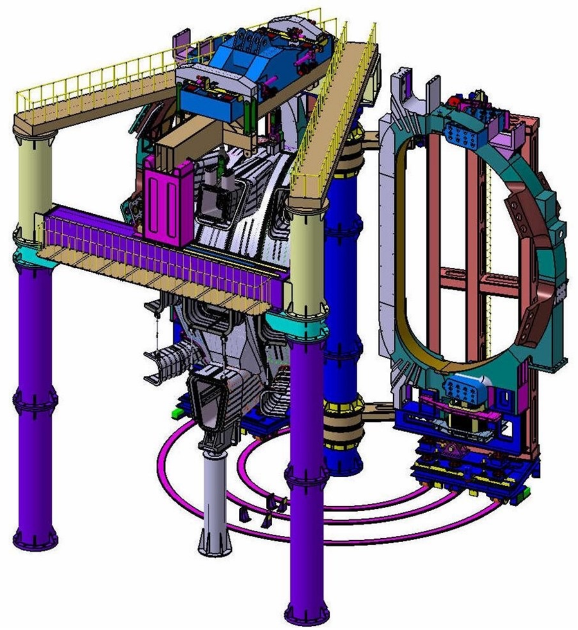
A crucial milestone



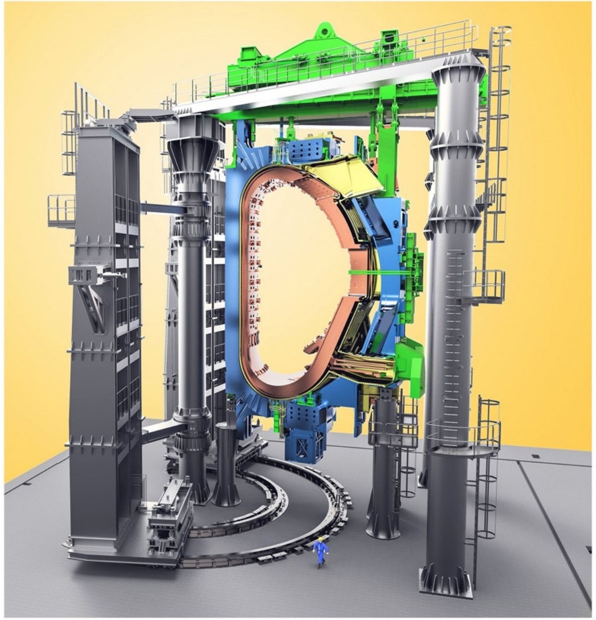
28 July 2020: remote celebration by 7 ITER Members Heads of State and French President

Sub-sector assembly

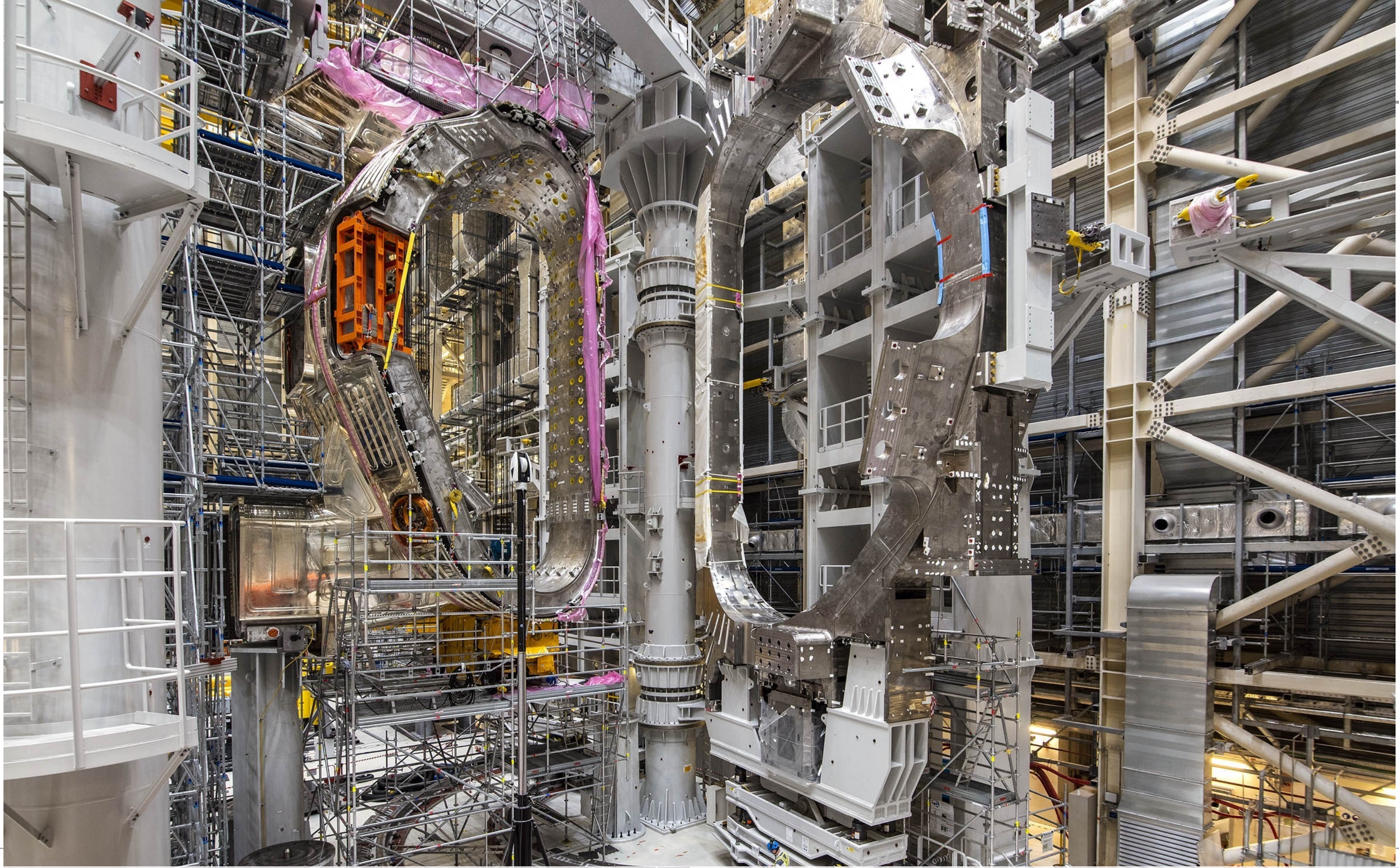
- Assembly of Vacuum Vessel, Thermal Shield and 2 Toroidal Field coils



TF Coil Assembly



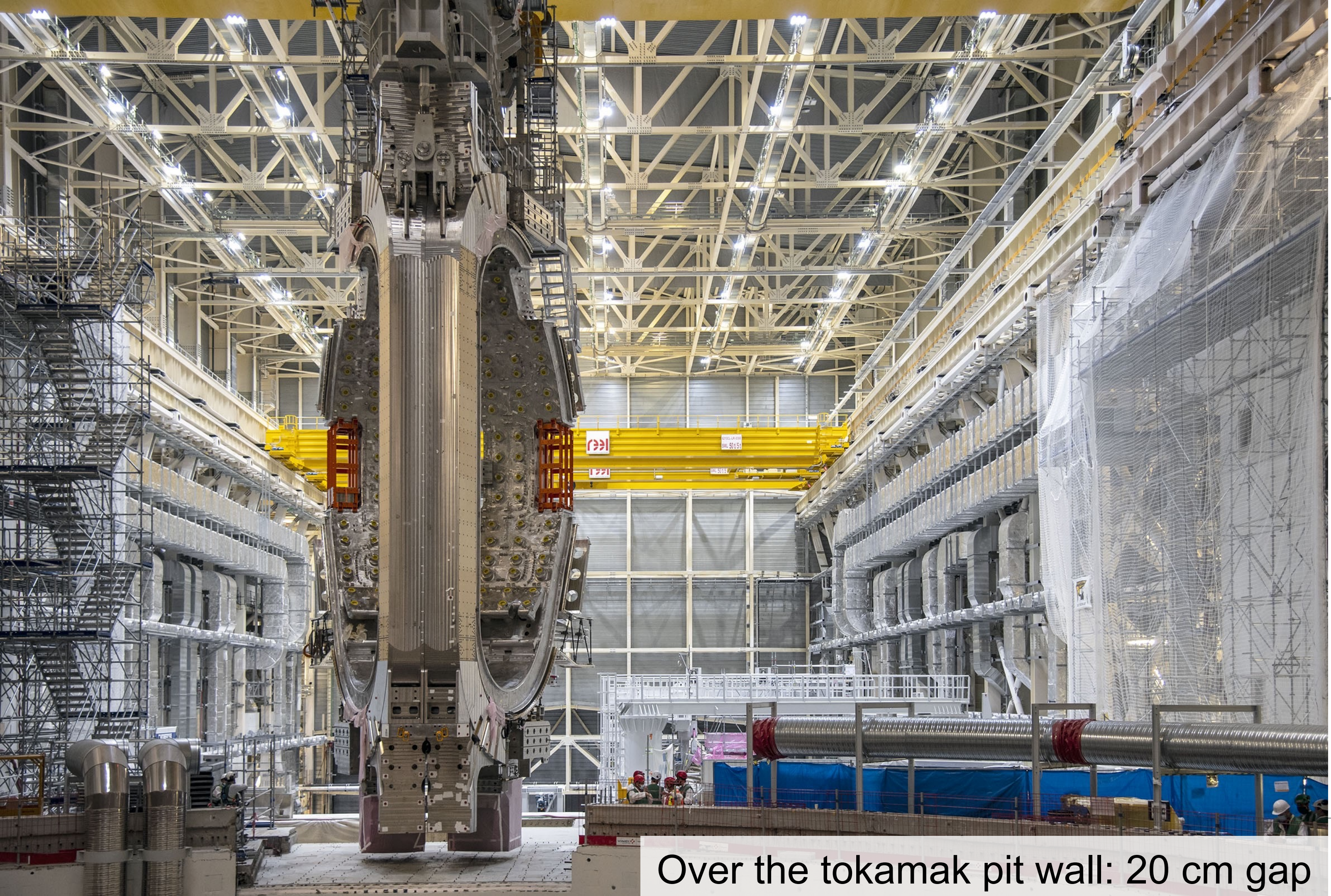
Finalized Sector Assembly before transfer to pit



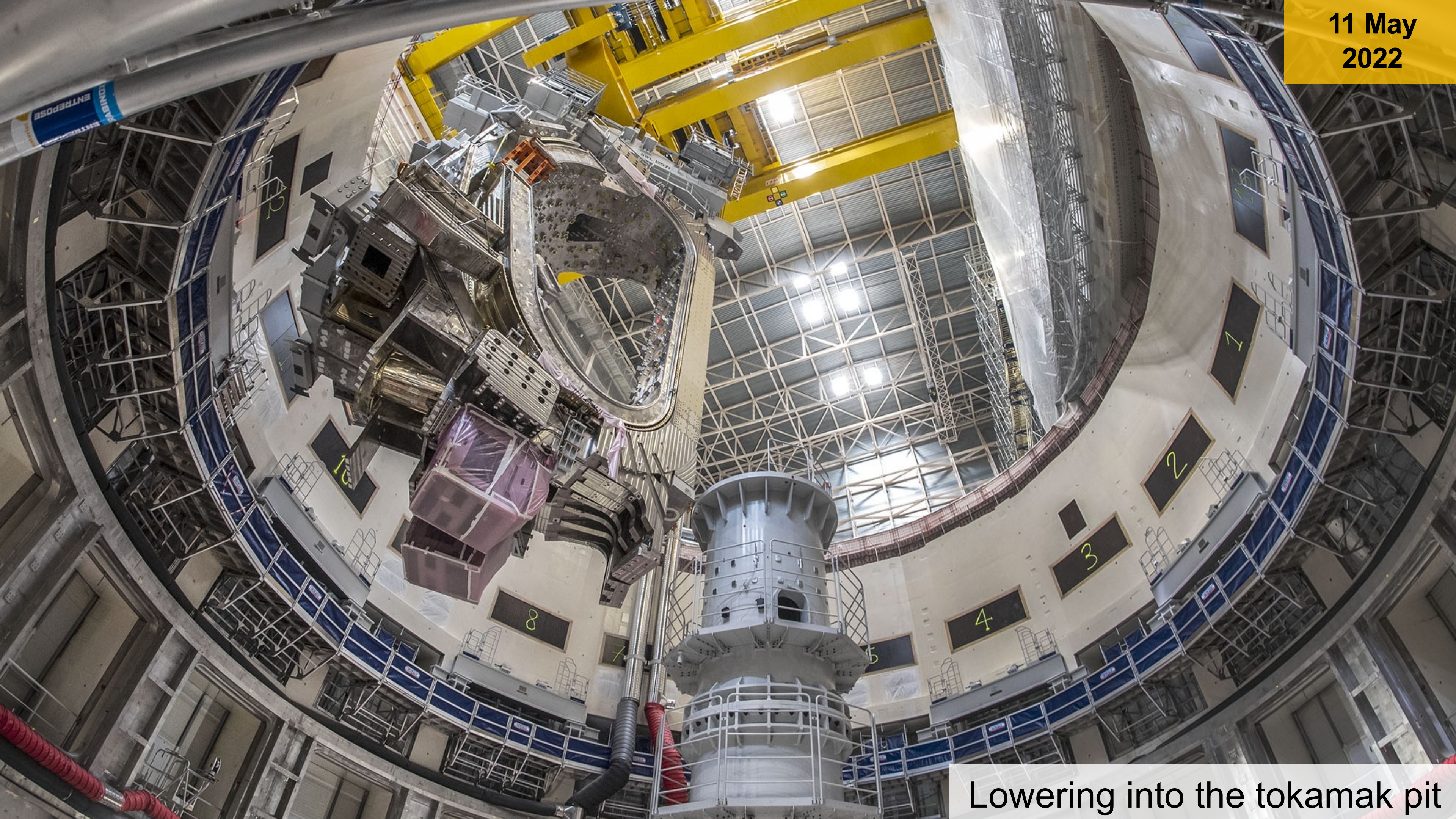
VV Sector 7 with TF coil 9 on right arm of SSAT-1

11 May 2022

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



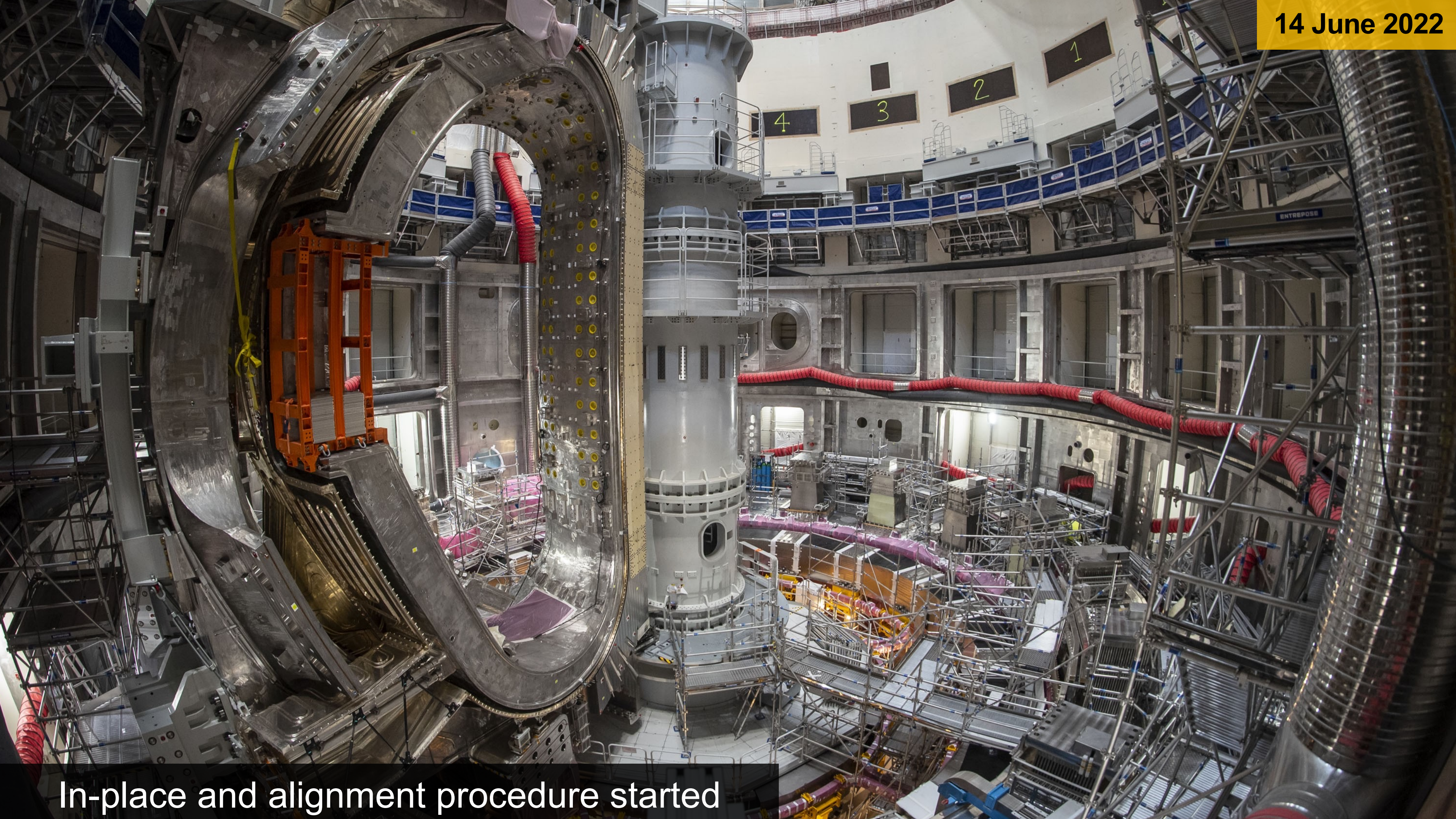
Over the tokamak pit wall: 20 cm gap



11 May 2022

Lowering into the tokamak pit

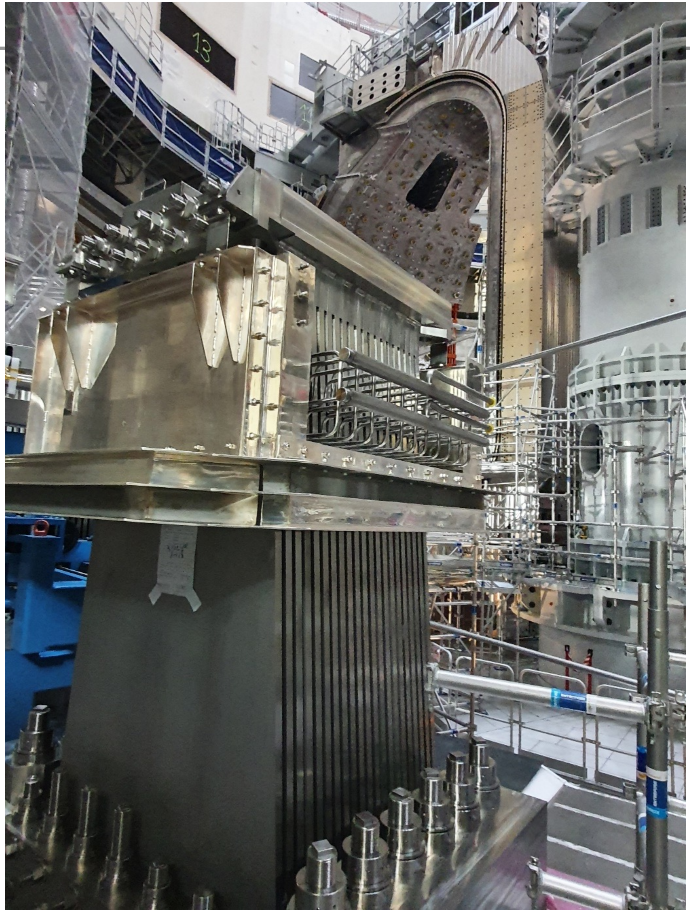
14 June 2022



In-place and alignment procedure started

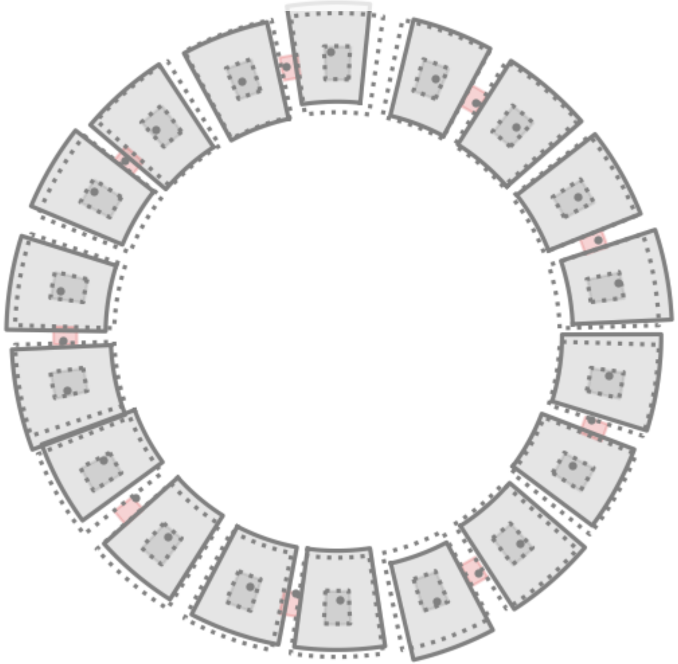
Alignment procedure completed

15 October 2022

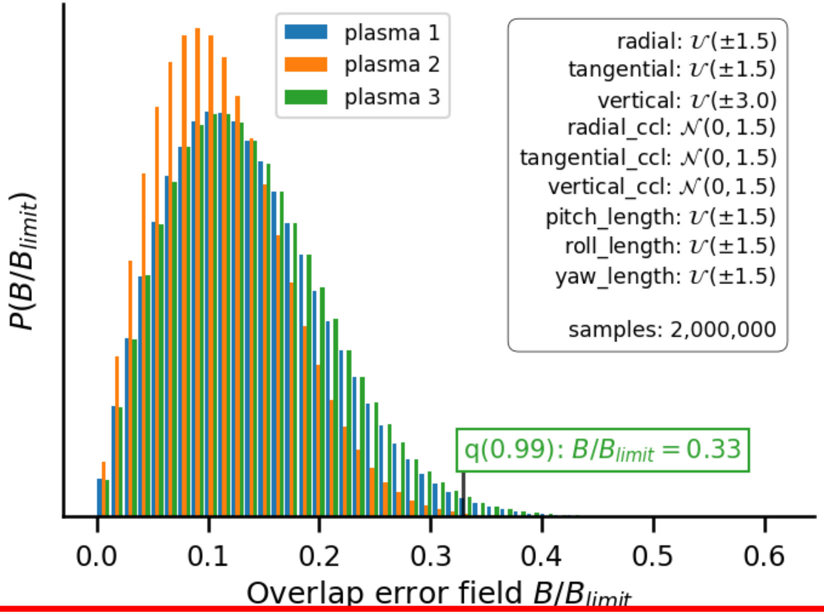


Alignment procedure guided by physics assessment of error fields

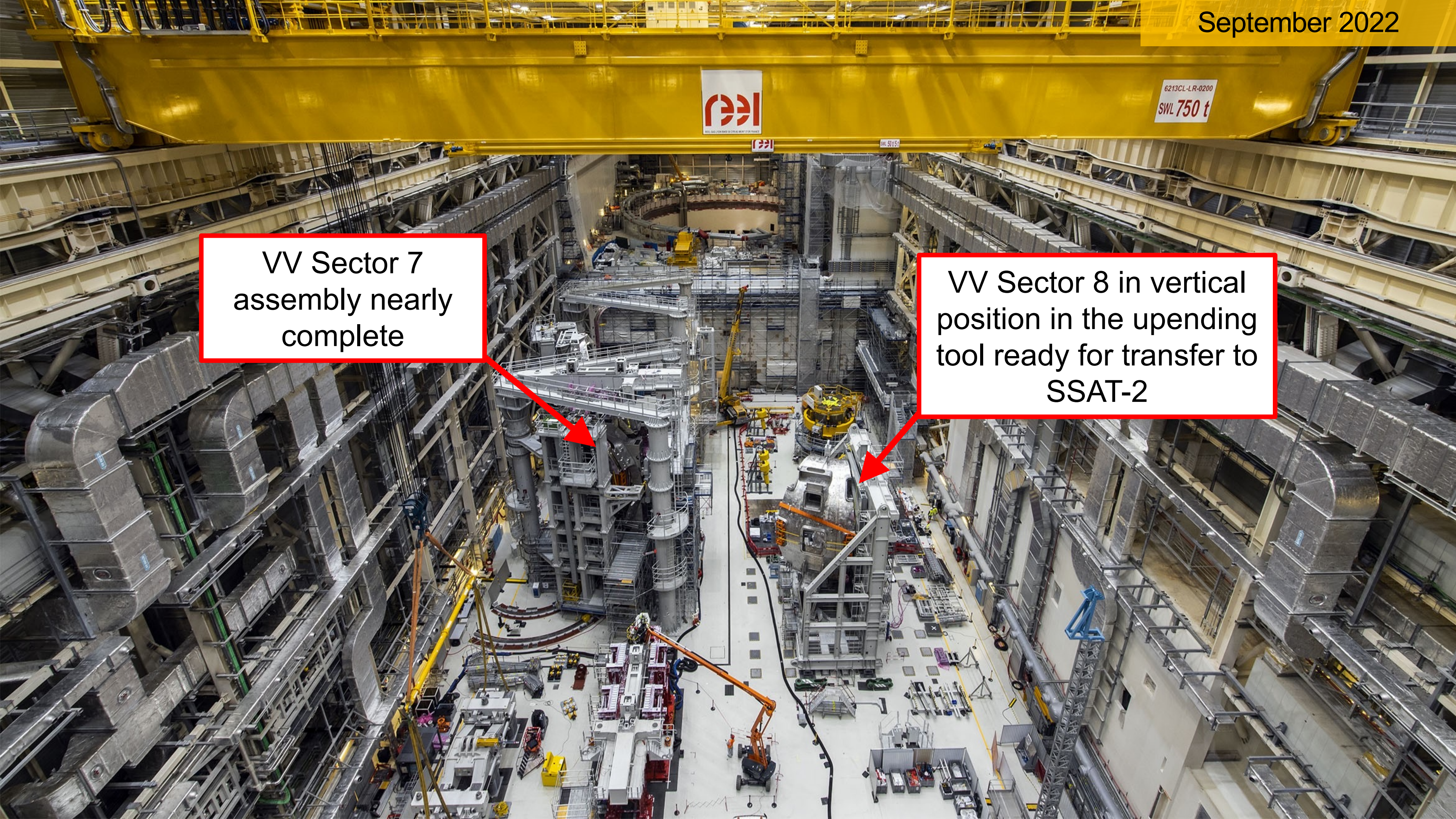
Alignment targets ensure that for 99% of the cases TF assembly will contribute less than 33% of the n = 1 overlap field (ITPA scaling)

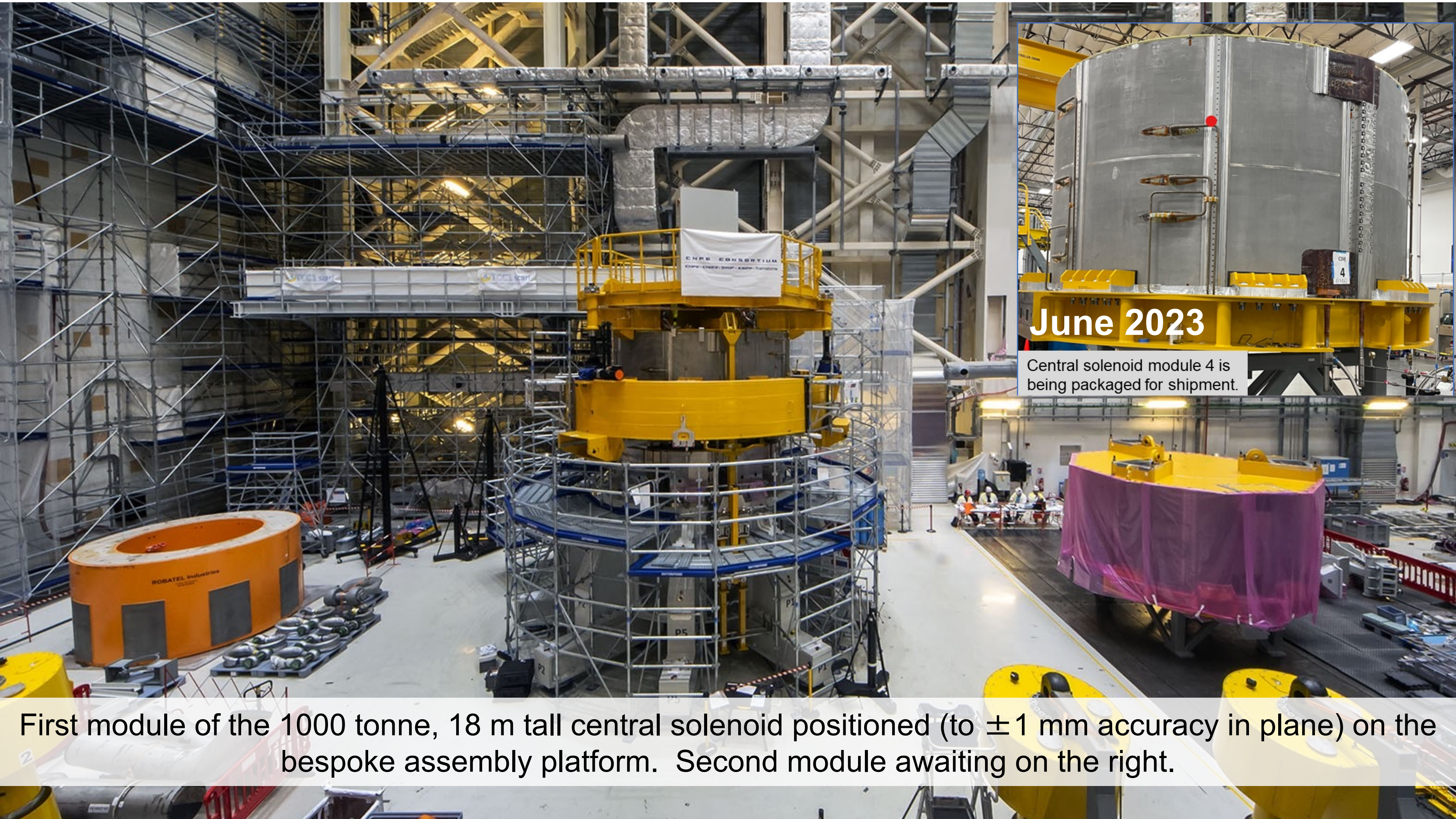


(15 MA/5.3T : plasma 1 SOF, plasma 2 EOB)



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


September 2022
VV Sector 7 assembly nearly complete
VV Sector 8 in vertical position in the upending tool ready for transfer to SSAT-2
6213CL-LR-0200
SWL 750 t



June 2023

Central solenoid module 4 is being packaged for shipment.

First module of the 1000 tonne, 18 m tall central solenoid positioned (to ±1 mm accuracy in plane) on the bespoke assembly platform. Second module awaiting on the right.

Issues found and solutions

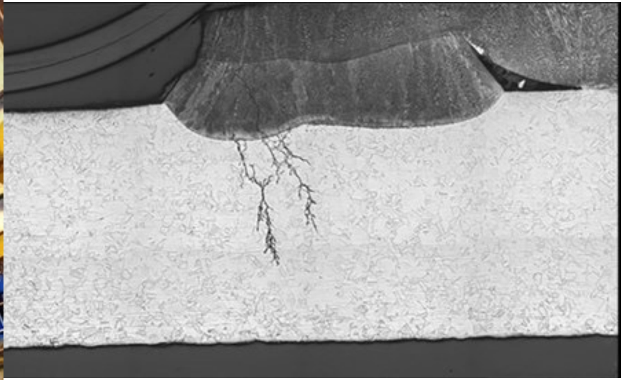
more details in

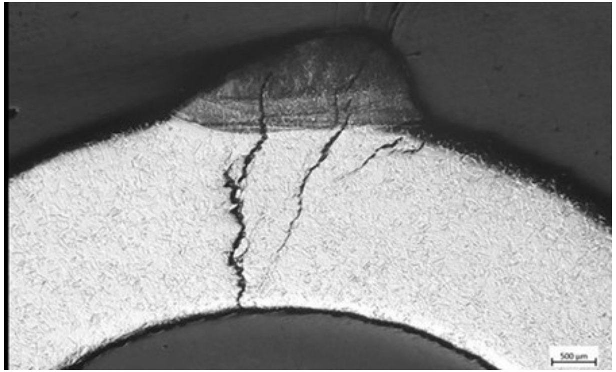
https://www.iter.org/newsline/-/3818

and

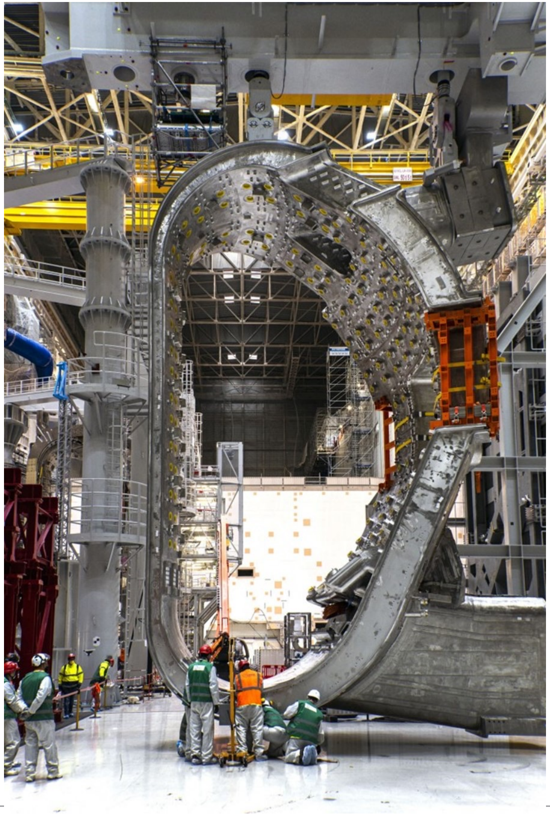
https://www.iter.org/newsline/-/3830

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)

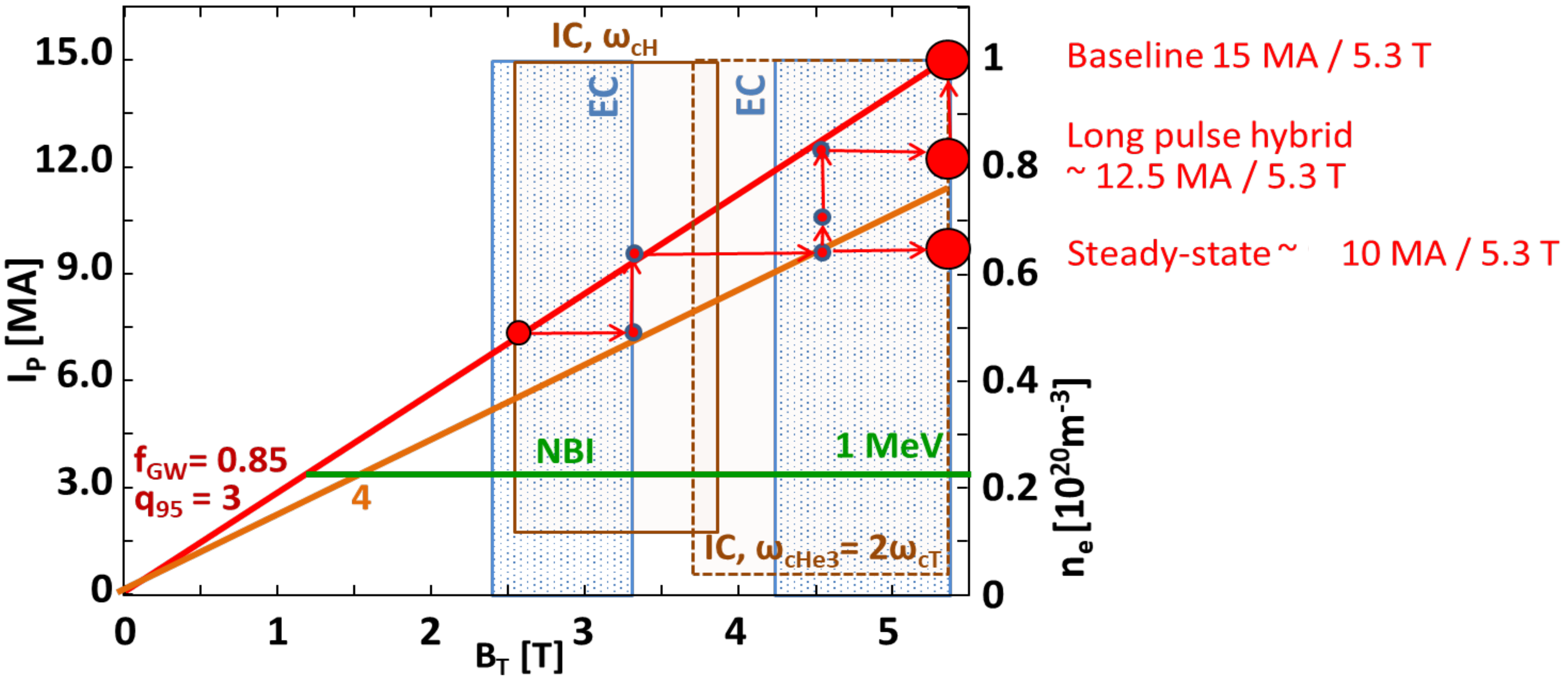
IRP describes strategy for R&D to achieve Project goals starting from First Plasma to Q = 10 (300-500 s),Q = 5 (1000 s) & Q = 5 steady-state

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

- **Initial phase H/He (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

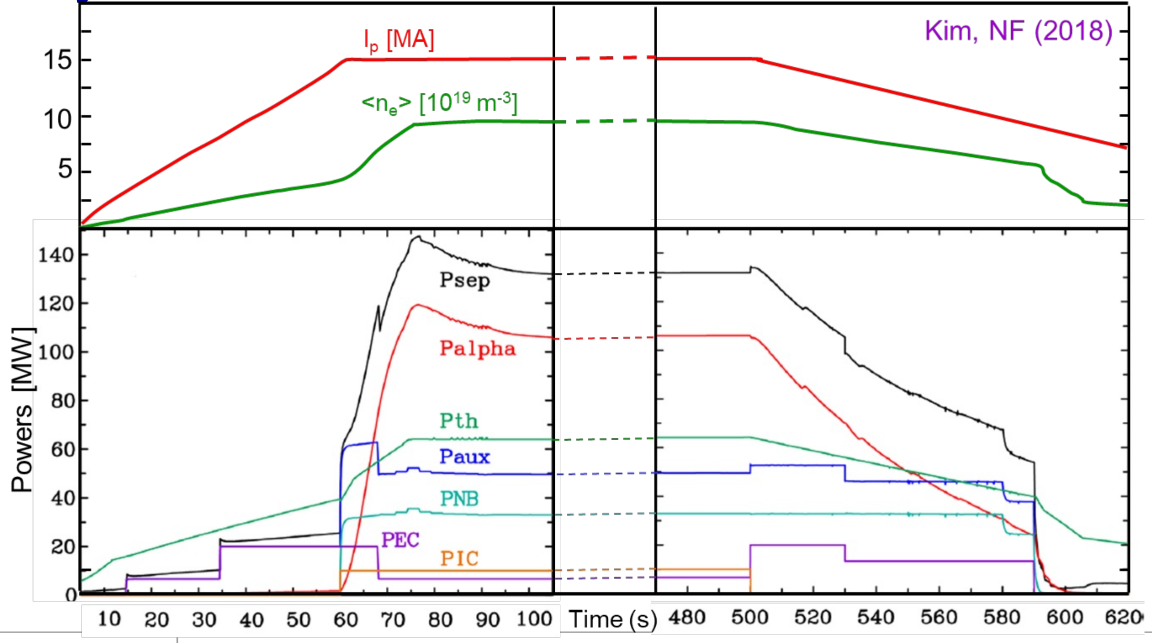
Fusion Power Operation (D/DT)



ITER burning plasma scenarios

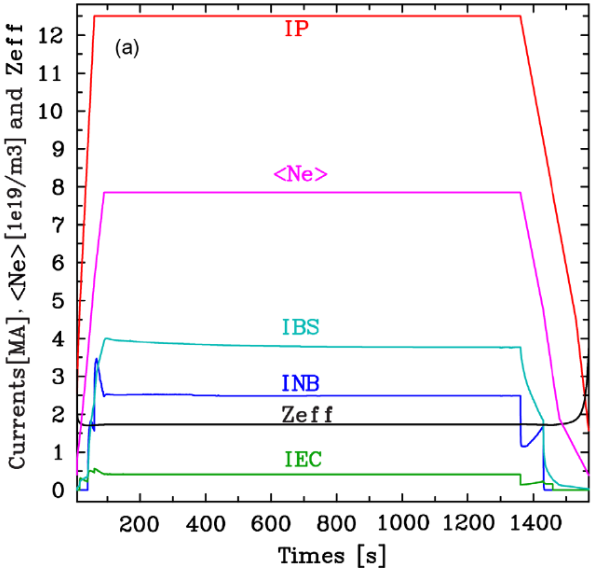
ITER Q = 10 scenario (300 – 500 s burn)

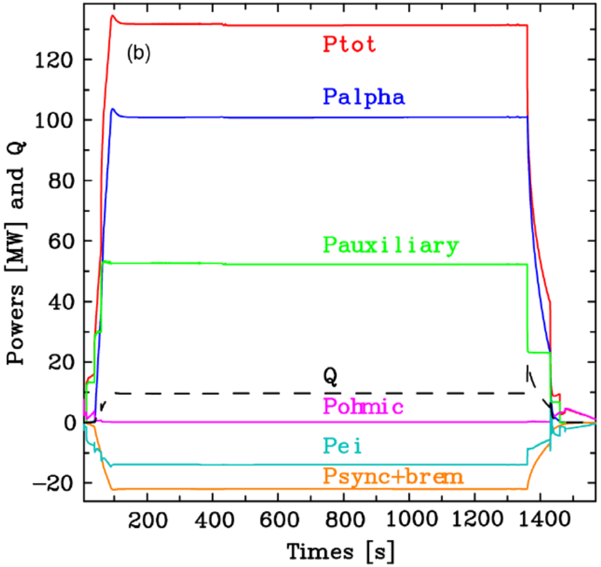
- Based on conventional sawtoothing H-mode with H_{98} = 1 → scenario used for the design of magnets and components (15 MA/5.3 T)
- $P_{aux} = P_{NBI} + P_{ECH}$ (+ P_{ICH}) ~ 50 MW → Alpha-heating dominant scenario with non-inductively driven current ~ 35%



ITER 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%

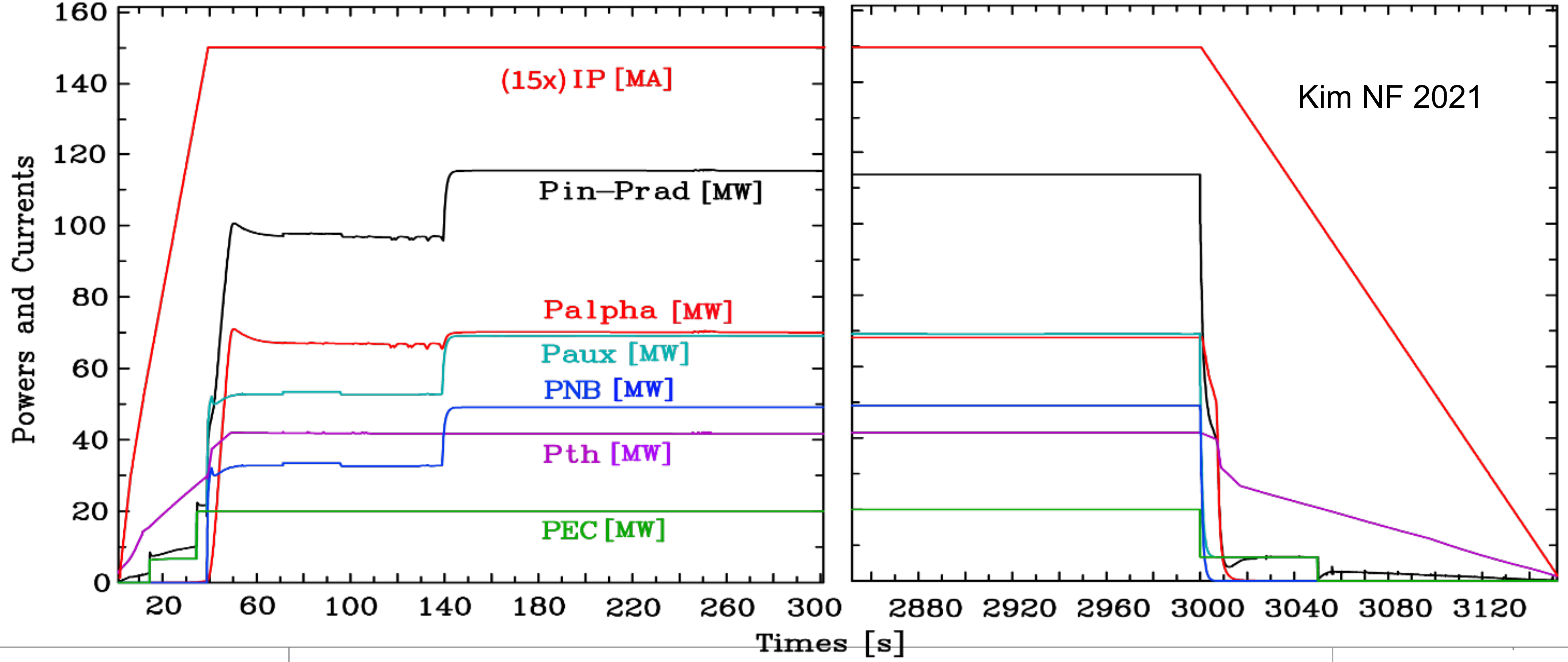




Kim NF 2016

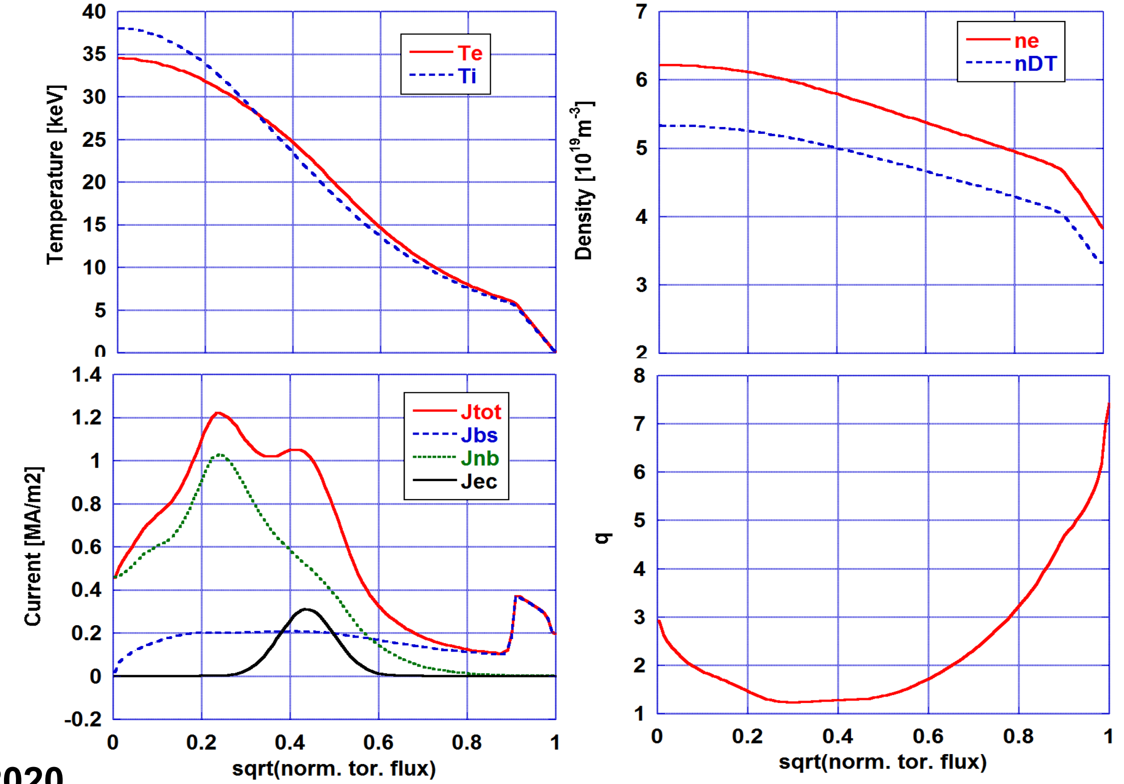
ITER Q ~ 5 scenario (steady-state)

- 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, β_N=3.02
  - q_{min}=1.23
  - Relatively high $l_i(3)$~0.87 mainly due to 50 MW NBI (+ 20-30 MW ECH)
  - Improved confinement is essential



Polevoi – NF 2020

Access to high Q conditions

- Access to high Q requires build-up of P_{alpha} 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})

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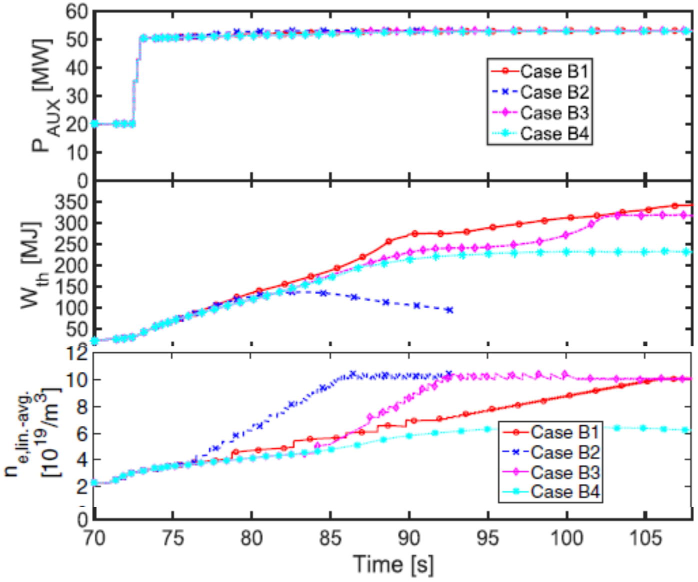
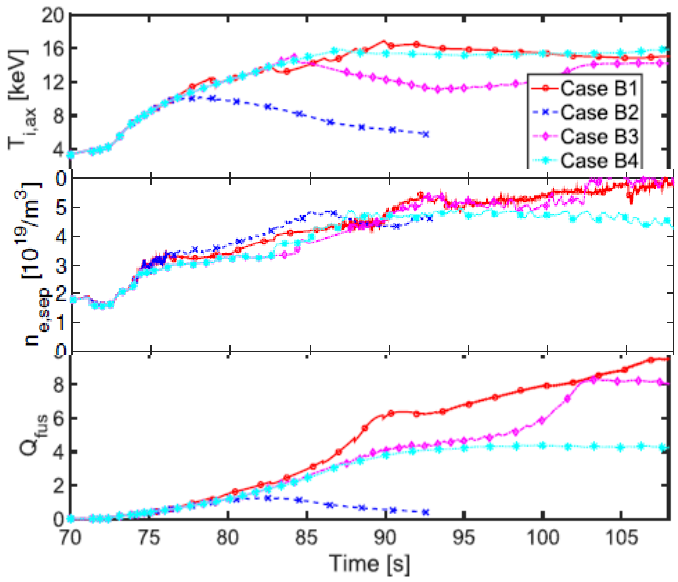
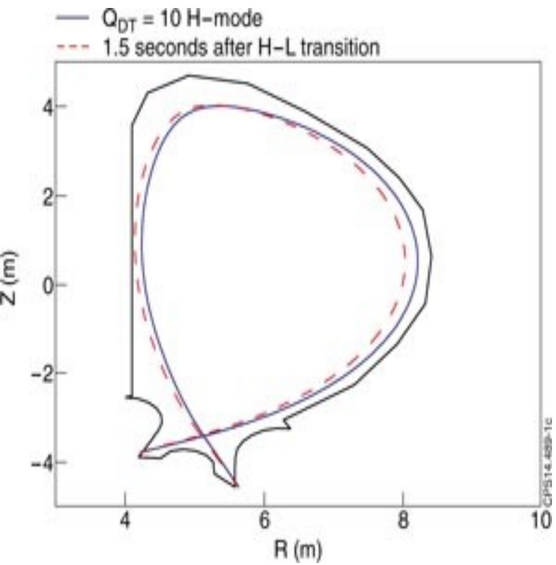




Exit from high Q conditions

- **Main issue in exit from high Q is to avoid fast H-L transitions → radial plasma movement difficult to control and large power fluxes to divertor**
- **Adjustment of P_{aux}, fuelling and Ne seeding required to lengthen W_{plasma} decrease phase and avoid too high q_{div} or too deep detachment**



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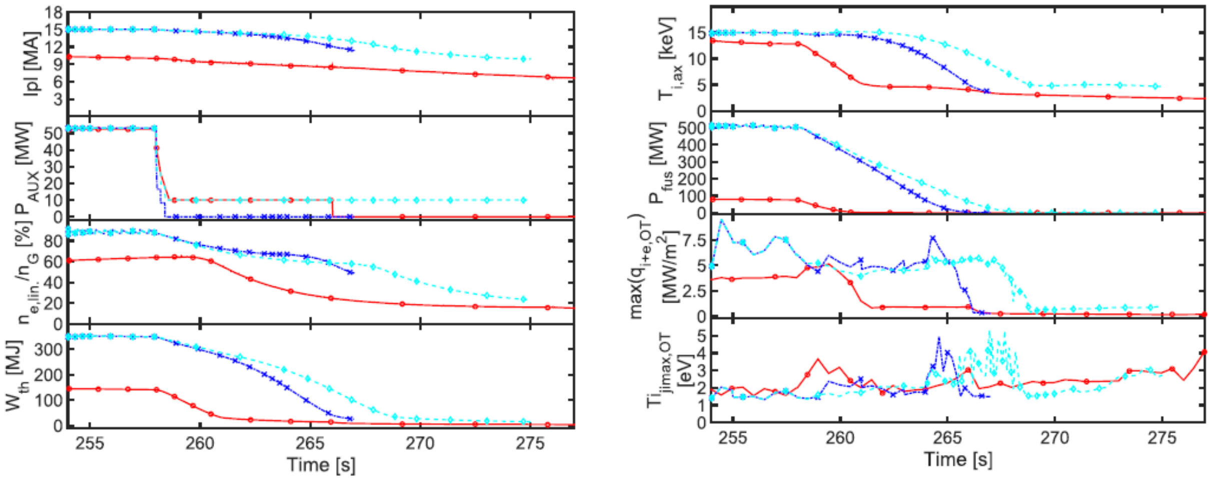


Energetic ions in ITER scenarios - I

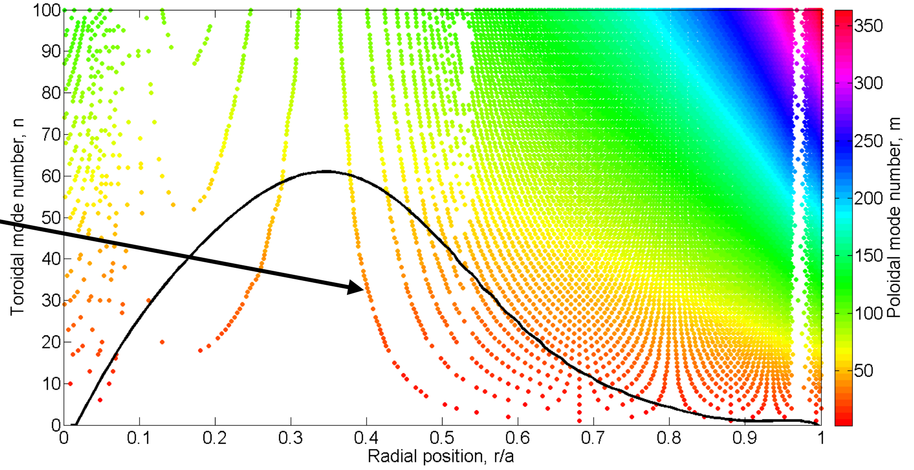
- Energetic ions impact on ITER burning plasmas
  - Can drive MHD Alfvén eigenmodes → energetic ion loss $P_\alpha \downarrow$ ☹
  - Can reduce anomalous transport level → higher τ_E → $P_\alpha \uparrow$ ☺
  - Can increase core plasma β and thus shafranov shift → increased edge stability/pressure → 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

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