Objectives and status of the ITER project, the first fusion reactor under construction

Alberto Loarte on behalf of
Science Division
Science, Controls, and Operation Department
ITER Organization

Outline of talk

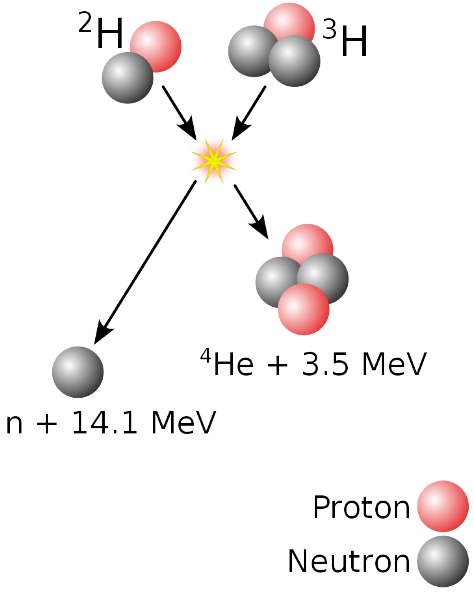
- ITER Mission, Basis, Goals, Scenarios and Overall Design
- ITER Project and Overview of Construction Status
- ITER Research Plan (IRP)
- Conclusions

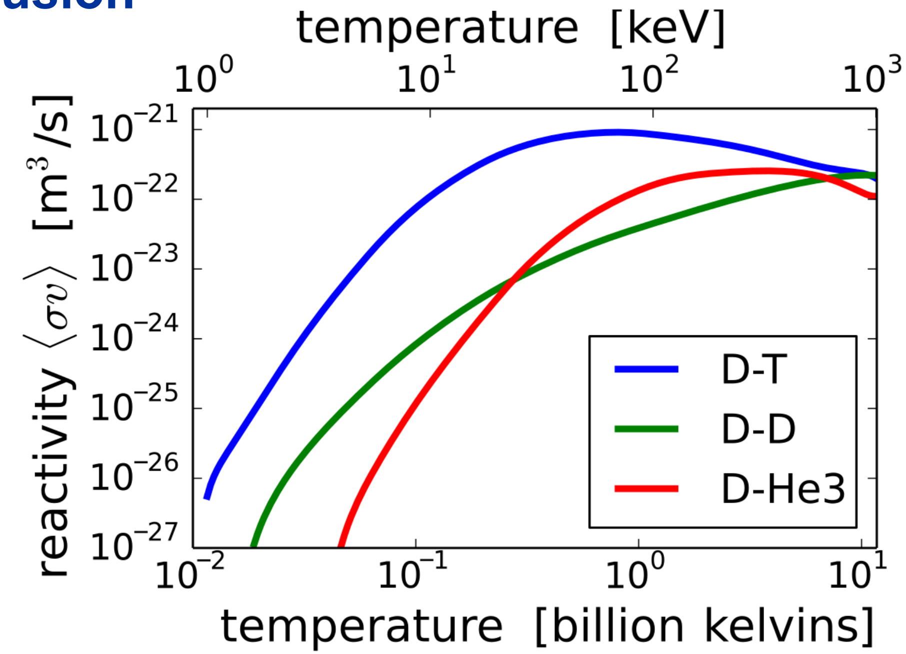
ITER Mission

ITER Mission

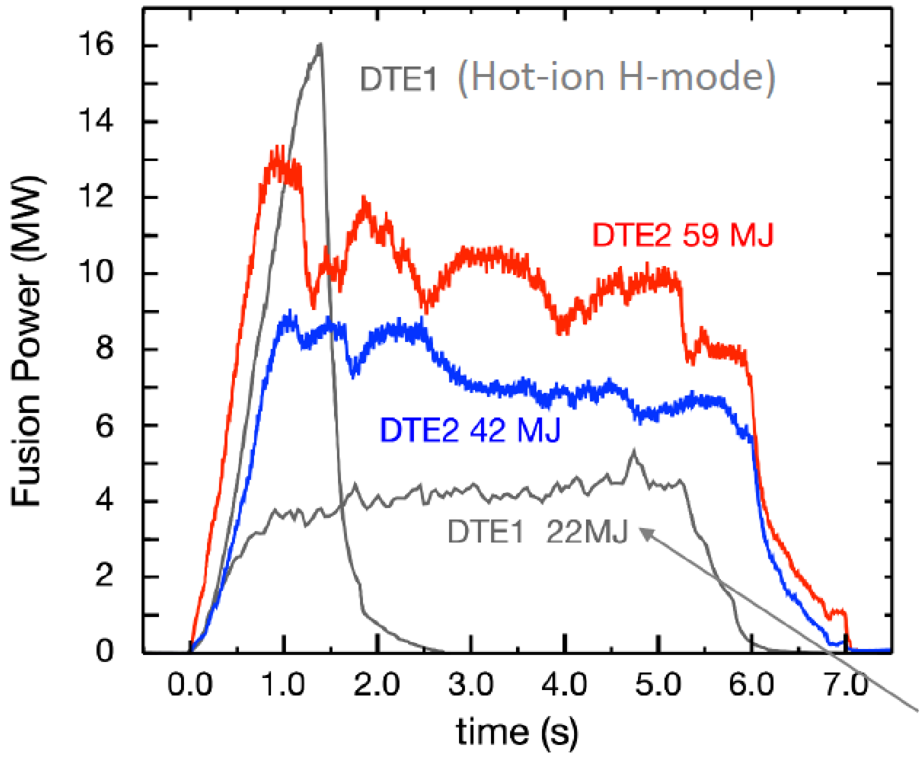
To demonstrate the scientific and technological feasibility of fusion power as energy source for humankind

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





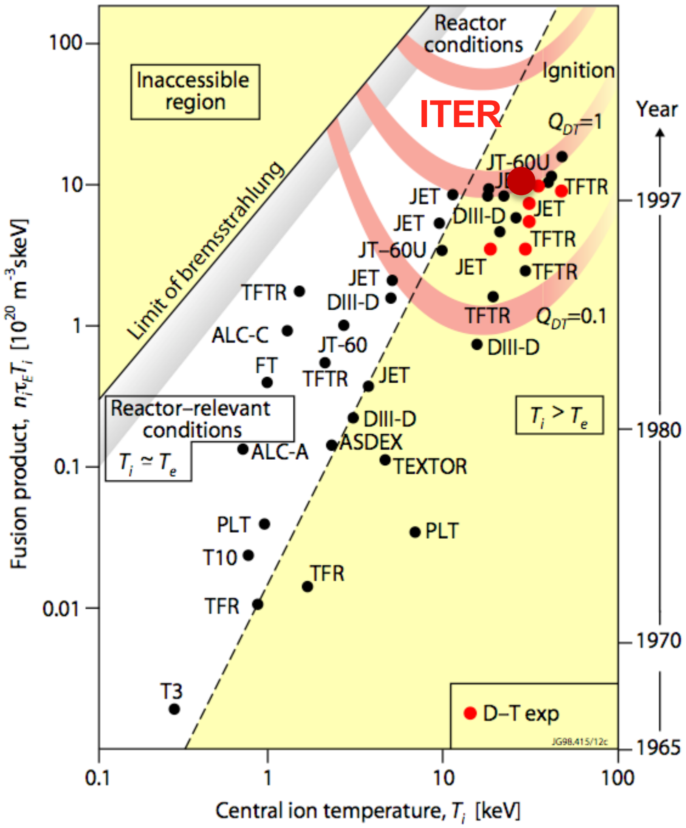
ITER Basis: DT Fusion Power Production



-heat

10

that



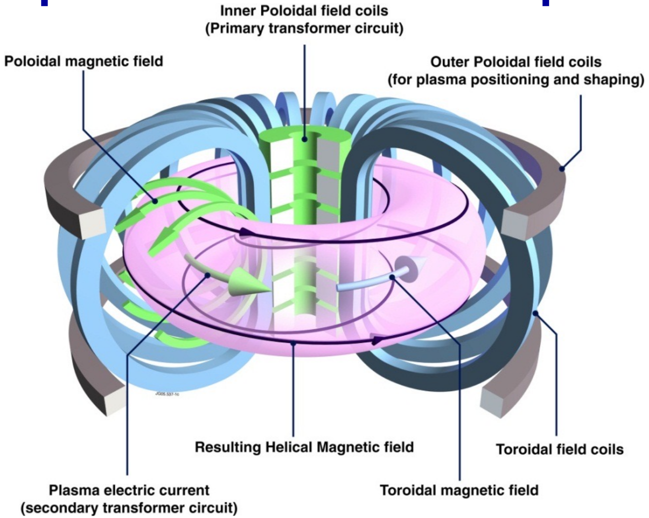
ITER Basis

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



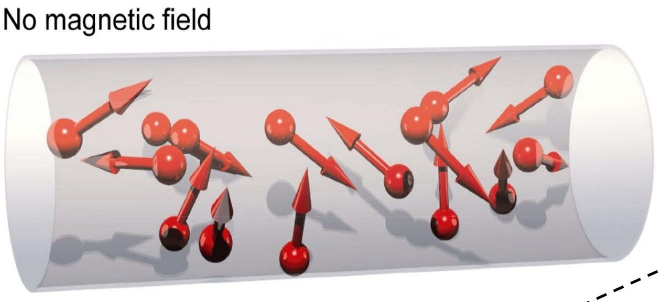
Tokamak

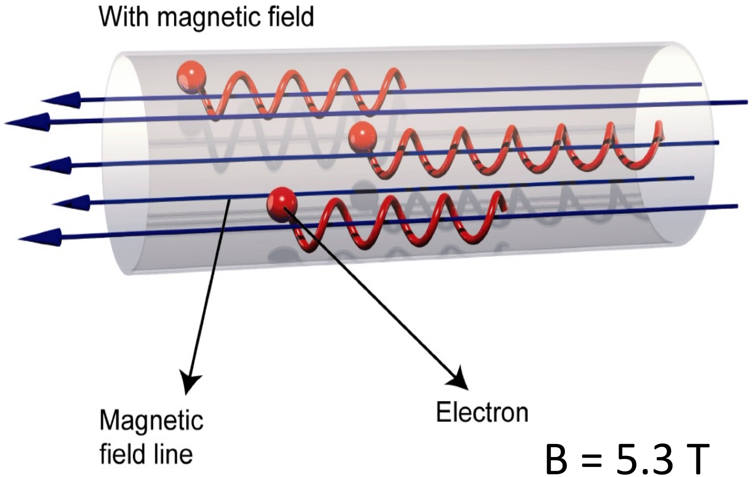
$$q = \frac{Toroidal\ turns}{Poloidal\ turns} \geq 2$$

Magnetic Confinement – Lorentz Force

- Magnetic fields force electrons and ion to rotate around them → No force $\parallel \vec{B}$

$$\vec{F} = q\,\vec{v} \times \vec{B}$$





Larmor radius (B = 5.3 T)

$$\rho = \frac{m v_{\perp}}{|q| B}$$

- e ~ 50 μm
- i ~ 3 mm

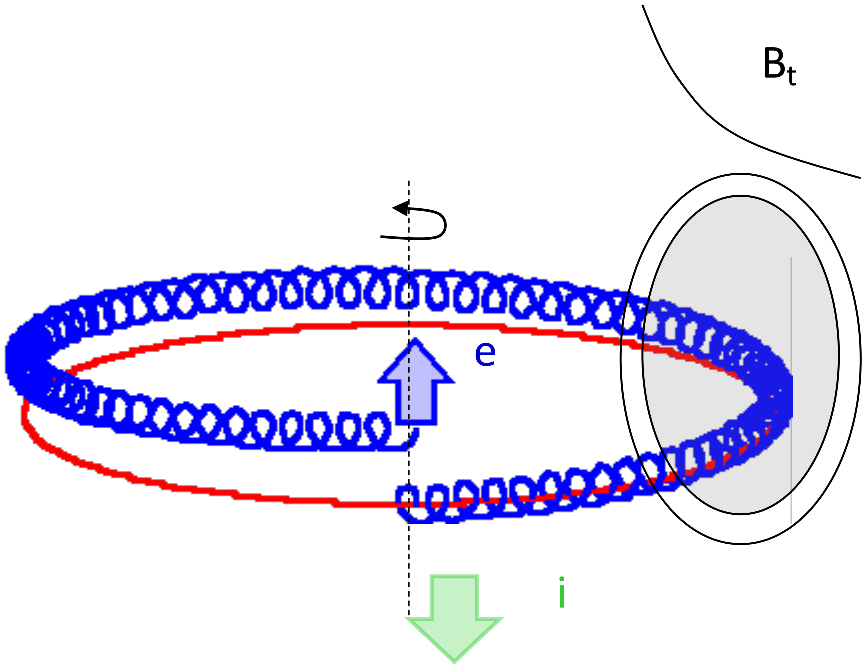
Cyclotron frequency (B = 5.3 T)

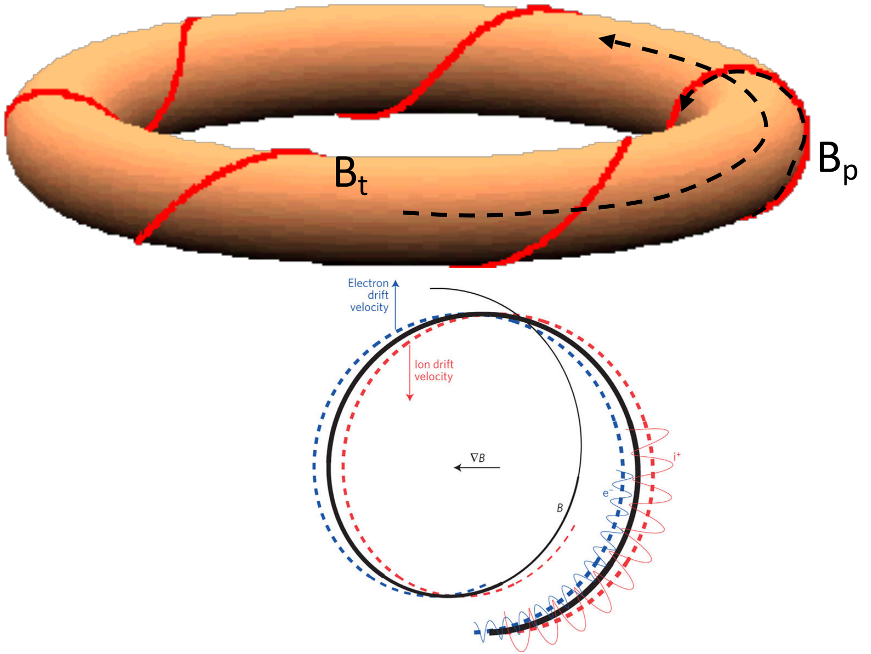
$$\omega = \frac{|q| B}{m}$$

- e ~150 GHz
- i ~ 40 MHz

Electron and ion trajectories in a torus - I

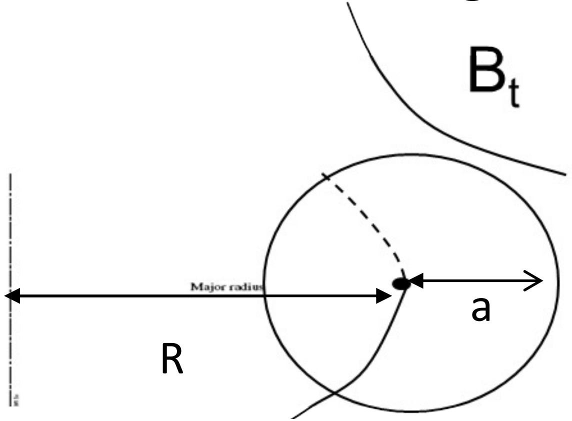
- Magnetic fields are closed into torus to prevent end losses
- Electrons and ions drift from toroidal field lines → helicoidal

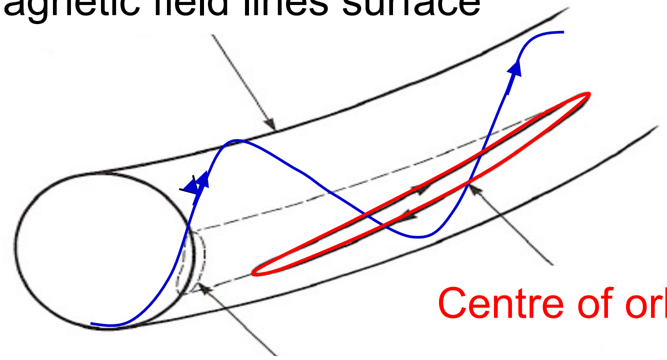


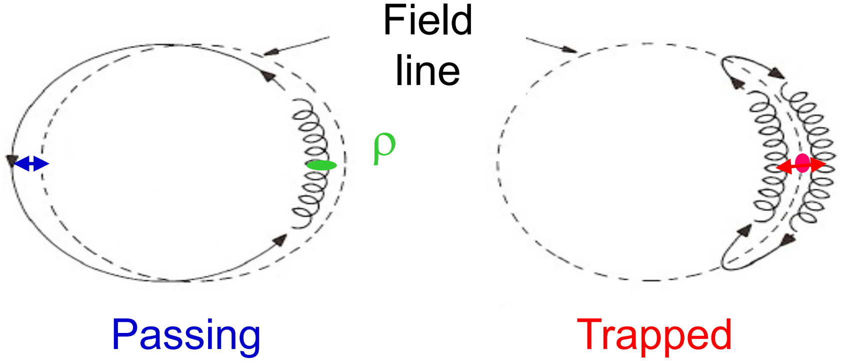


Electron and ion trajectories in a torus - II

- Toroidal helical magnetic affect particle trajectories







$\delta r_p = a/R \; B_t/B_p \; \rho < 3 \rho$ (tokamak)

$\Delta r_t = \sqrt{(a/R)} \; B_t/B_p \; \rho < 5 \rho$ (tokamak)

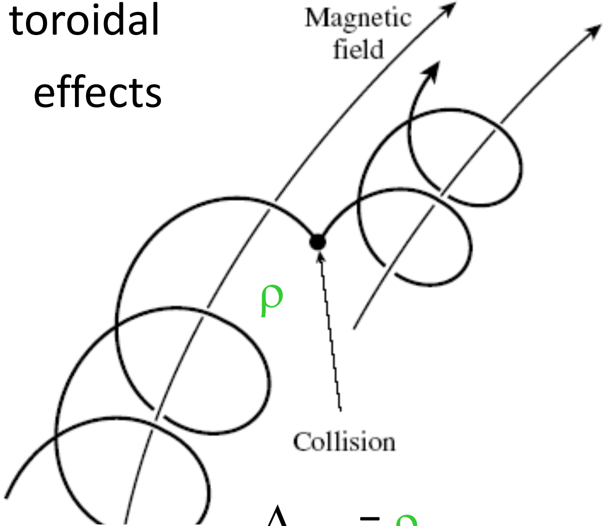
Collisions and Energy/Particle losses

- Collisions between particles are zeroth-order mechanism for plasma to lose energy → $\tau \sim a^2/D$

$$D \sim \Delta_{step}^{2} \times f_{coulomb}$$

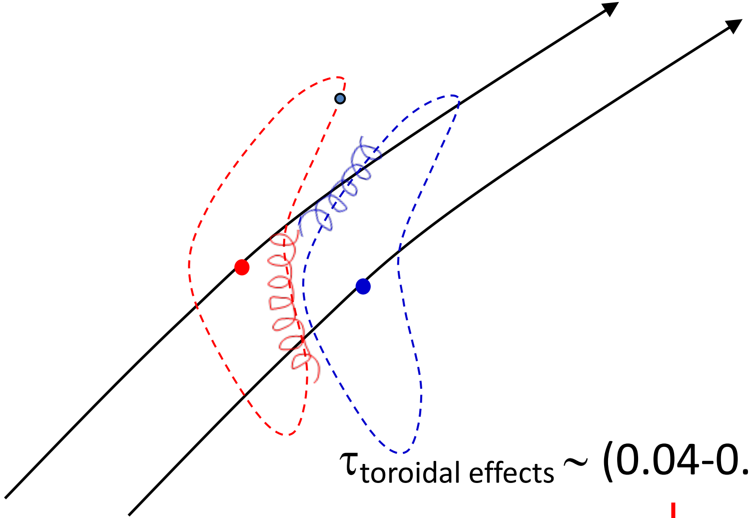
Low T

No toroidal effects



$\Delta_{step} = \rho$

High T



Toroidal effects

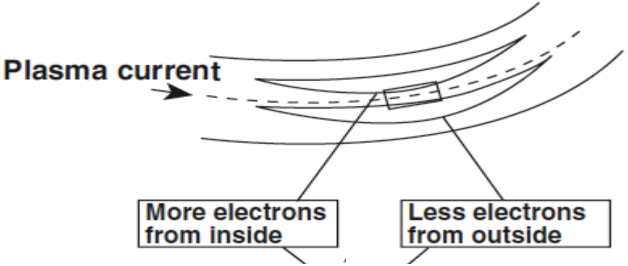
$\Delta_{step} = (3\text{-}5)\ \rho$

$\tau_{toroidal\ effects} \sim (0.04\text{-}0.1) \times \tau_{n.t.e.}$

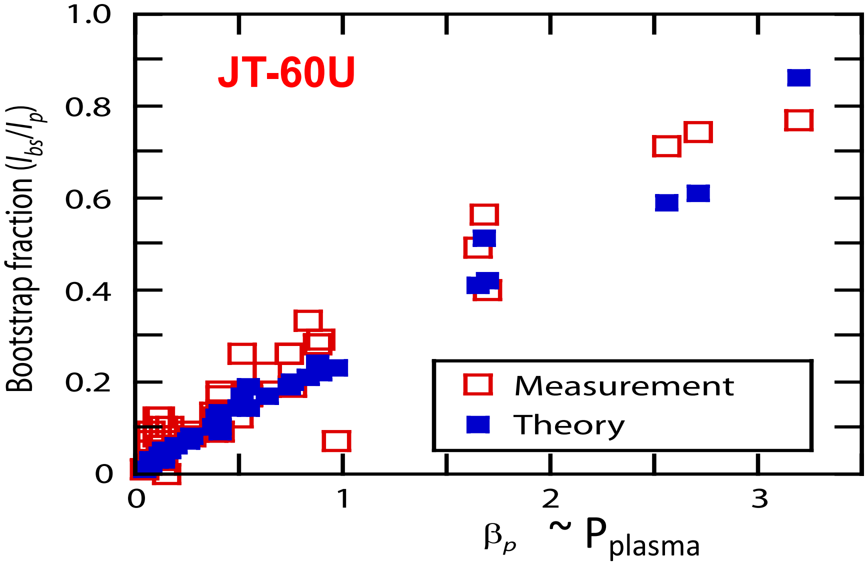
Neoclassical transport ~ laminar flow

Neoclassical Transport → Bootstrap current

- Gradients of density and temperature in the plasma can drive a current due to neoclassical effects → bootstrap current



$J_{bs} \sim -1/B_p \times dp/dr$

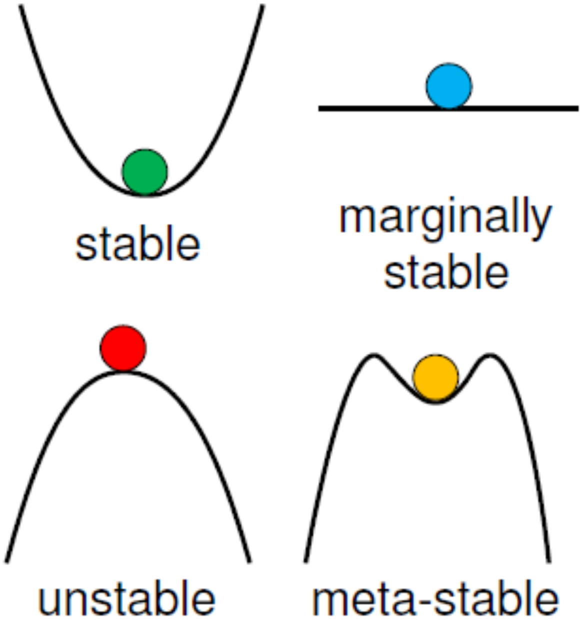


Bootstrap current is a key ingredient to achieve Q = 5 steady-state operation in ITER

Tokamak equilibrium stability

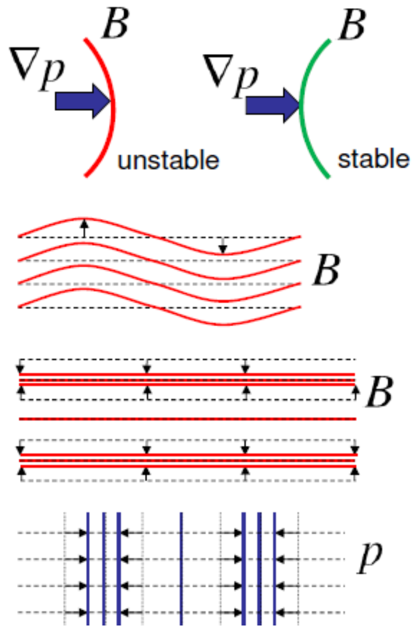
- Equilibria not always unstable → short life for unstable equilibria !

$$\mathbf{j} \times \mathbf{B} = \nabla p$$



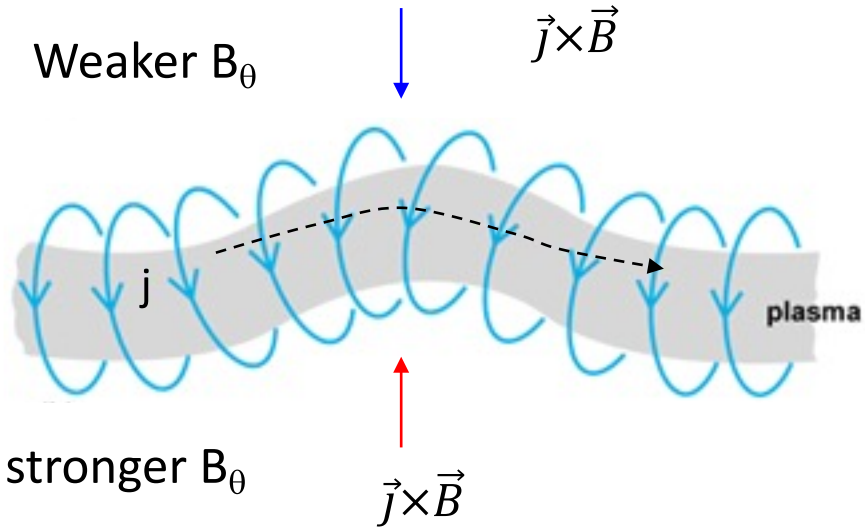
Stabilising/destabilising mechanisms

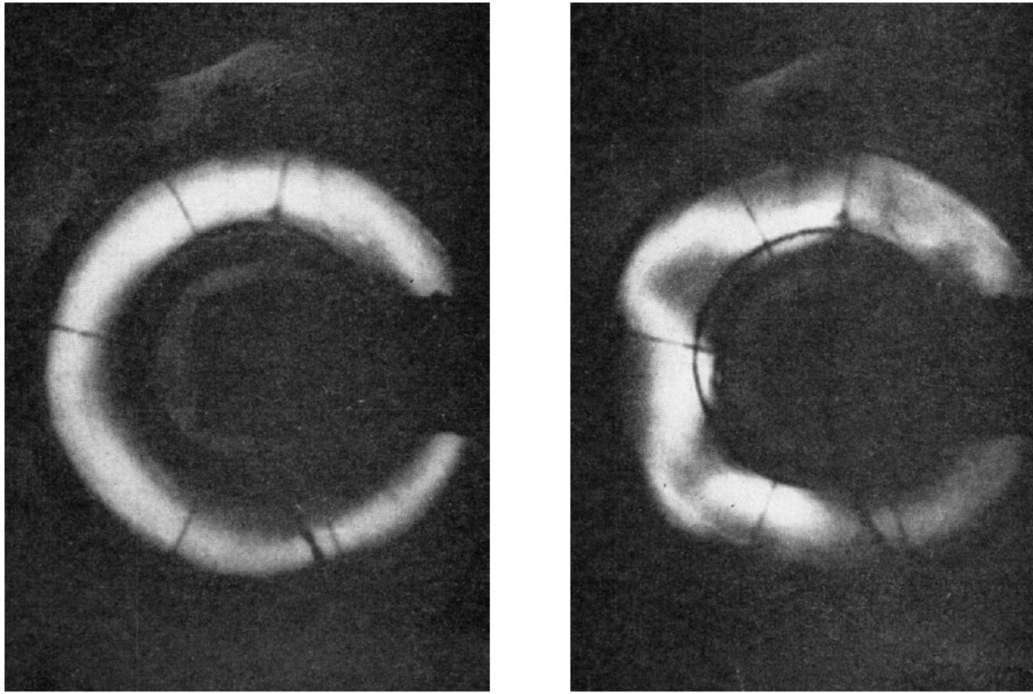
- Destabilising :
  - Plasma current (current gradient)
  - Pressure gradient ∇p
    - depending on field line curvature
- Stabilising :
  - Bending of magnetic field lines
    - Alfven waves
  - Compression of magnetic field lines
    - Fast (magneto-acoustic) waves
  - Compression of plasma
    - Sound (or slow magneto-acoustic) waves



Current driven instabilities

- Current driven instabilities (kink) globally distort plasma

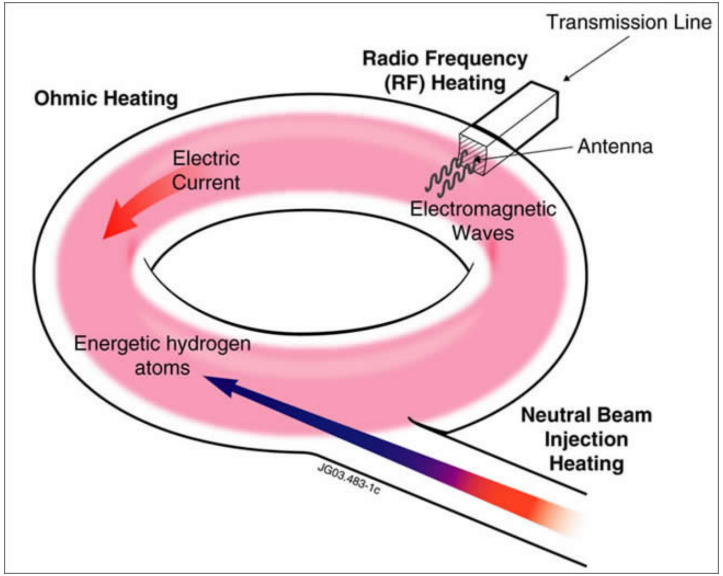




ITER Basis: Plasma Heating

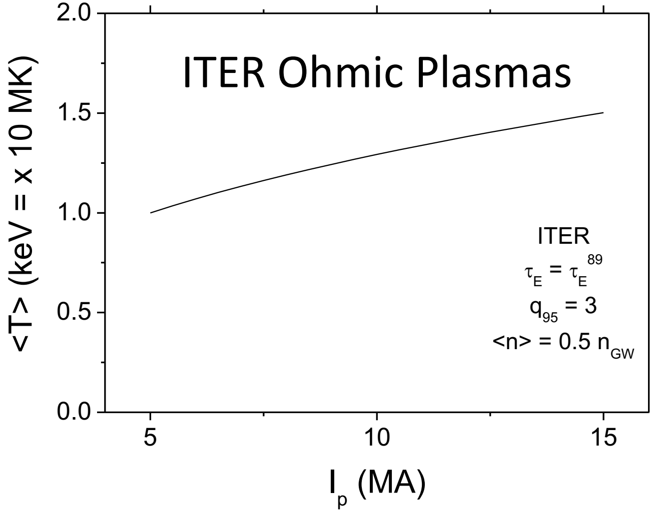
To achieve fusion power production T ~ 10 keV → Heating of Plasma is required :

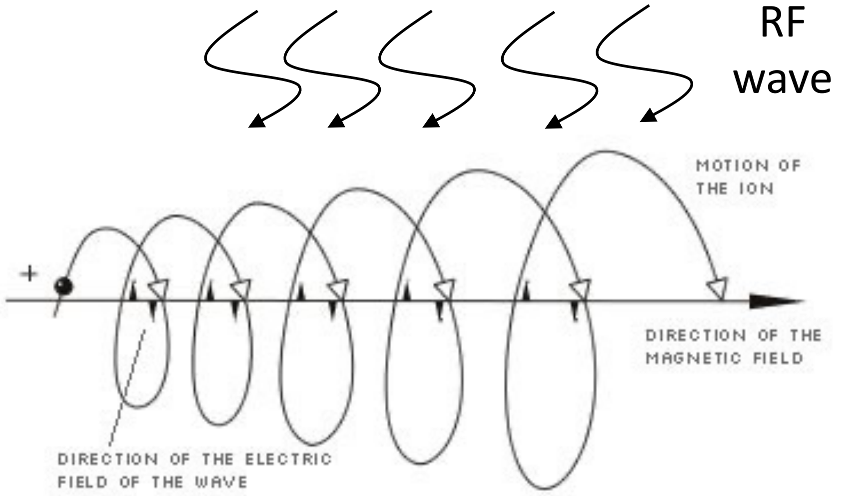
- **Ohmic heating = $I_p^2 R_p$; $R_p \sim T^{-3/2}$ → insufficient**
- **Radio Frequency Heating**
- **Injection of energetic atoms**



Plasma heating (Ohmic, ICRH, ECRH, NBI, α)

- Ohmic heating cannot reach T ~ 10 keV ($R \sim T^{-1.5}$) → additional heating
- Two principles : resonant absorption of RF on electrons/ions (ICRH/ECRH) and injecting/producing energetic (fast) ions in plasma (NBI, α-heating)



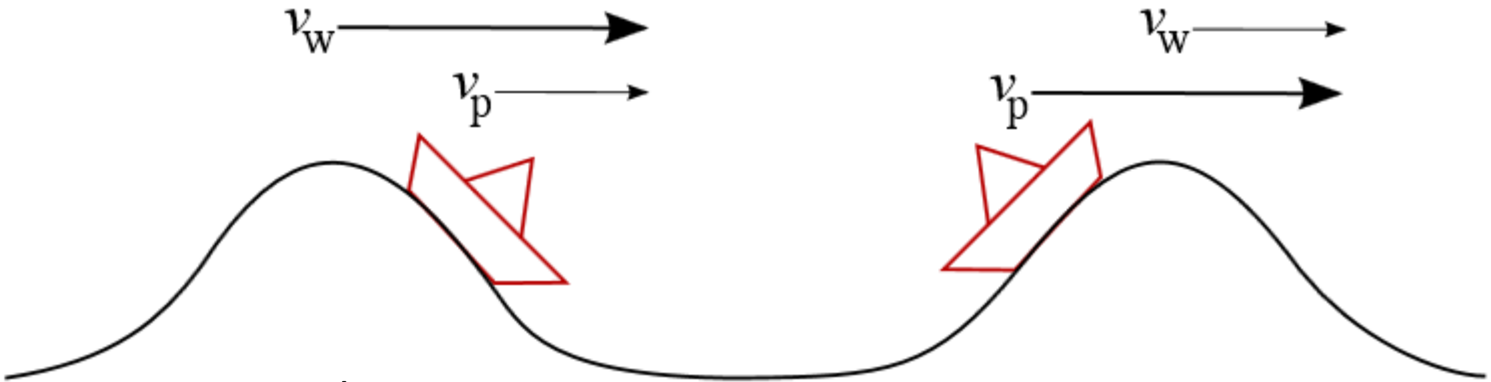


Transfer of heat from hot ions to plasma by coulomb collisions to thermal e & i

$\sigma_{Coulomb} \sim (v_{fast\text{-}ion} - v_{th.e,i})^{-4}$ → hot ions tend to heat electrons ($v_{fast\text{-}ion} >> v_{th.i}$)

Fast Particle Instabilities

- Fusion plasmas contain a large number of fast particles : α (3.5 MeV), NNBI (1 MeV), ICRH-accelerated ions (~ 100's keV)
- Fast particles can interact with waves in the plasma and can trigger instabilities



Particles gains energy from wave

Particles gives energy to wave

ITER Goals and overall design

ITER Goals

To demonstrate the scientific and technological feasibility of fusion power for peaceful purposes

- **Pulsed operation:**

  $Q \geq 10$ 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:**

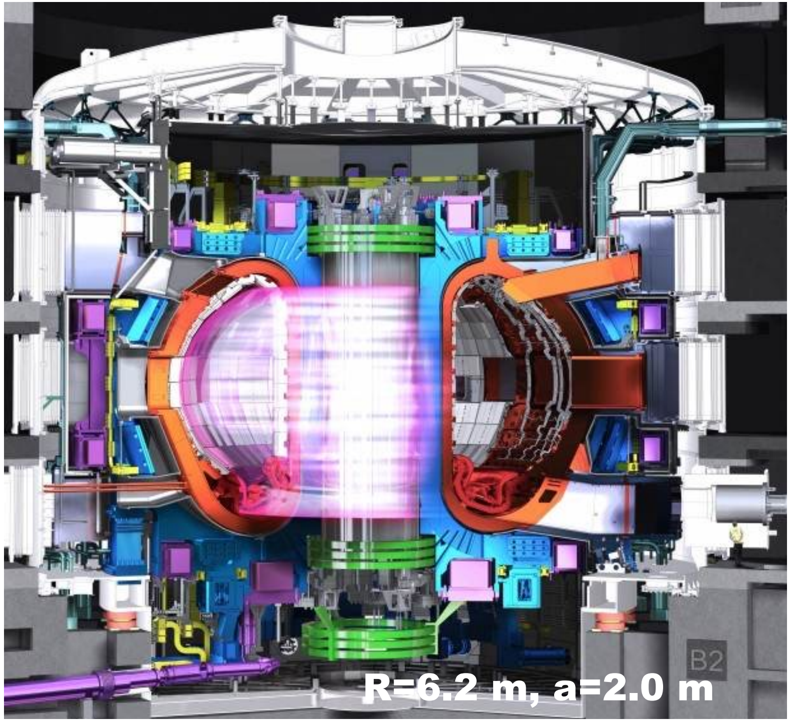
  Q ~ 5 for long pulses up to 1000 s

  → 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

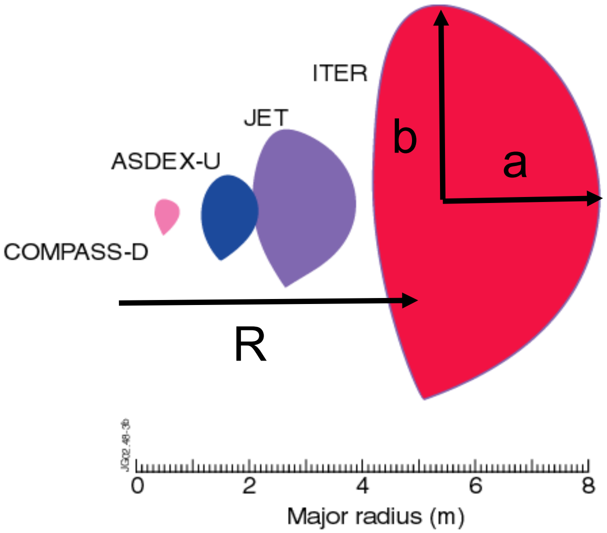
  → Steady-state scenario ~ 10 MA / 5.3 T

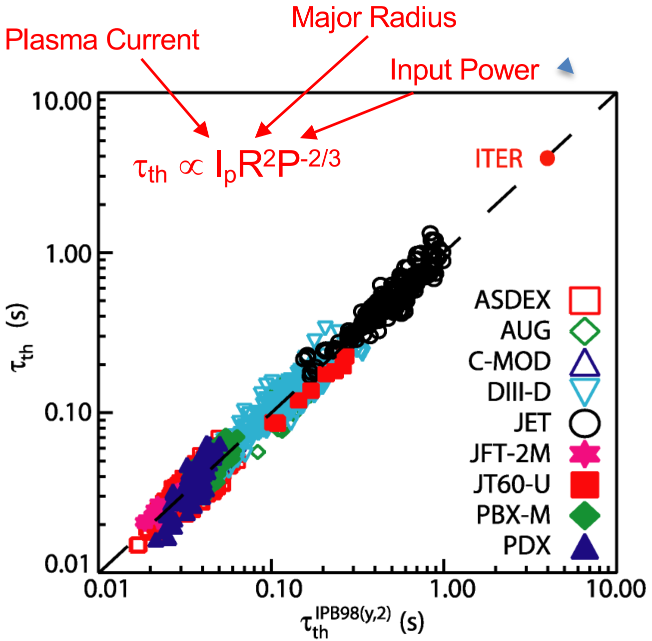


ITER Basis: Energy Confinement (τ_E)

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

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





$$q_{95} = 3$$

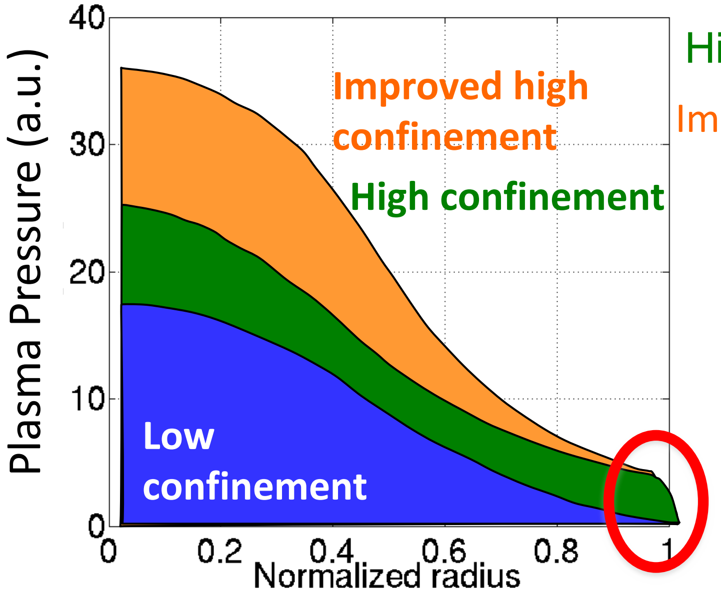
$$q_{95} = 2.5 \frac{a^2 B}{RI} f(\varepsilon, \kappa, \delta)$$

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

Access and sustainment of high confinement plasmas

❑ Achievement of high energy confinement plasmas

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



Low confinement (L-mode): pulsed operation ($H\sim0.5$)

High confinement (H-mode): pulsed operation ($H\sim1$)

Improved high confinement: long pulse ($H\sim1.2$) / steady-state ($H\sim1.6$)

Power threshold for transition from L to H-mode:

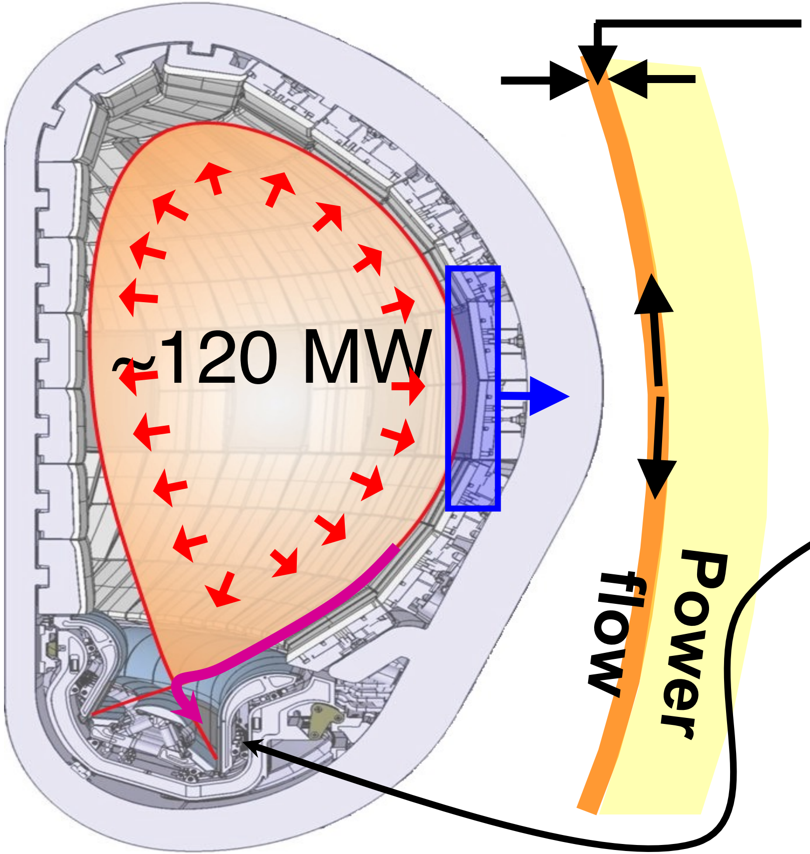
$$P_{L-H} \propto n_e^{0.7} \times B^{0.8}$$

(empirical basis)

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

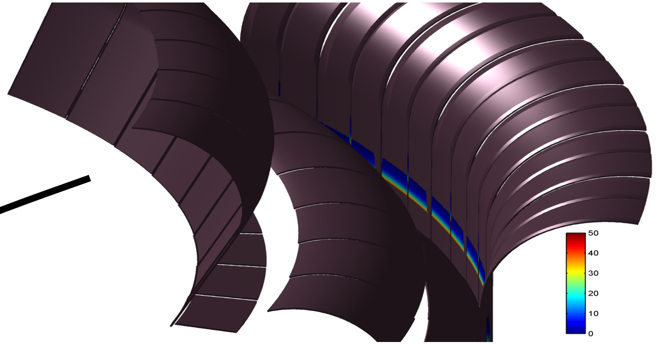
$$P_{L-H}(\boldsymbol{He}) \sim P_{L-H}(\boldsymbol{H}) \;/\; 1.5$$

Power loads to Plasma Facing Components



We expect the "thickness" (λ_q) for SOL power flow will be only a **few mm** on ITER

$A_{effective}$ ~ 1-2 m^2



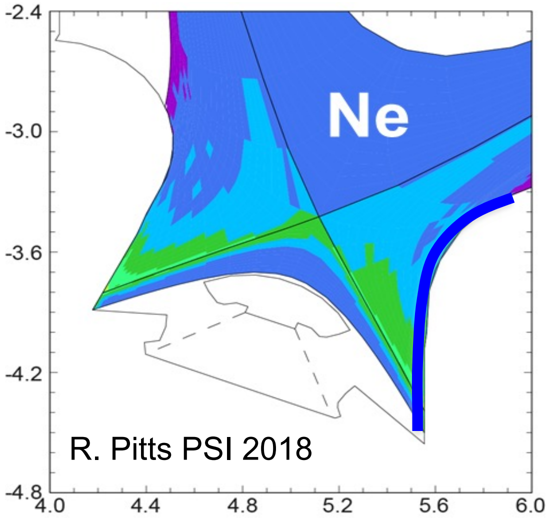
q_{div} ~ 50 MWm^{-2} → similar to heat flux on sun's surface (60 MWm^{-2})

$q_{divertor\text{-}design}$ ~ 10 MWm^{-2} → then what?

Edge-Core Integration

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

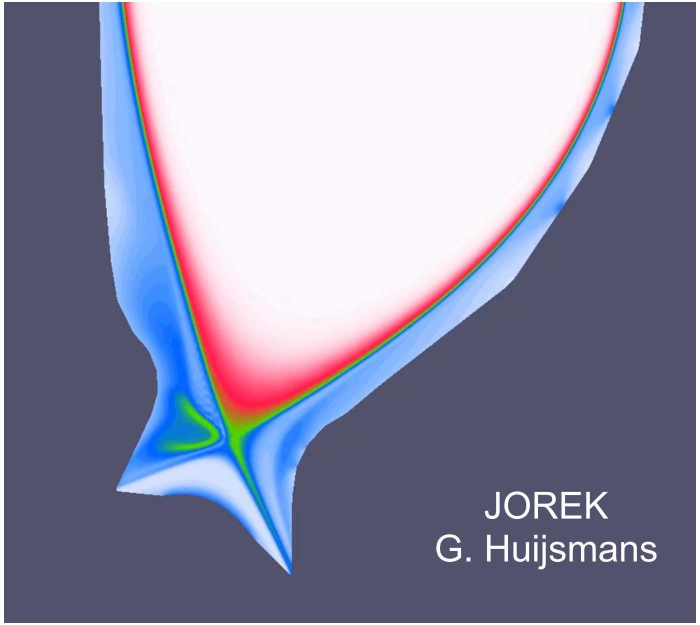
Radiative Dissipation



$P_{RAD,DIV}$ = 56.6 MW

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

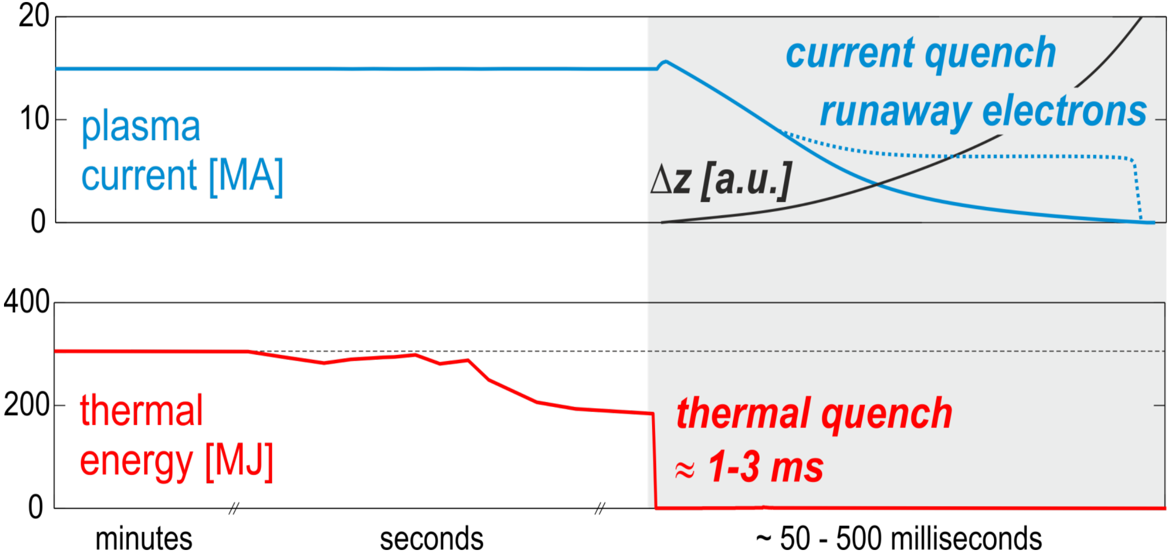
ELM control : Mitigation by f_{ELM} increase and suppression

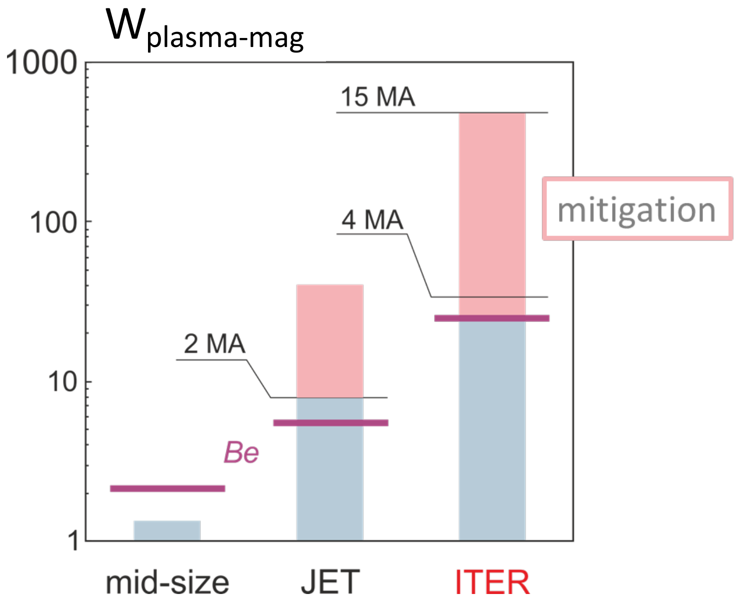


MHD stable operation + mitigation

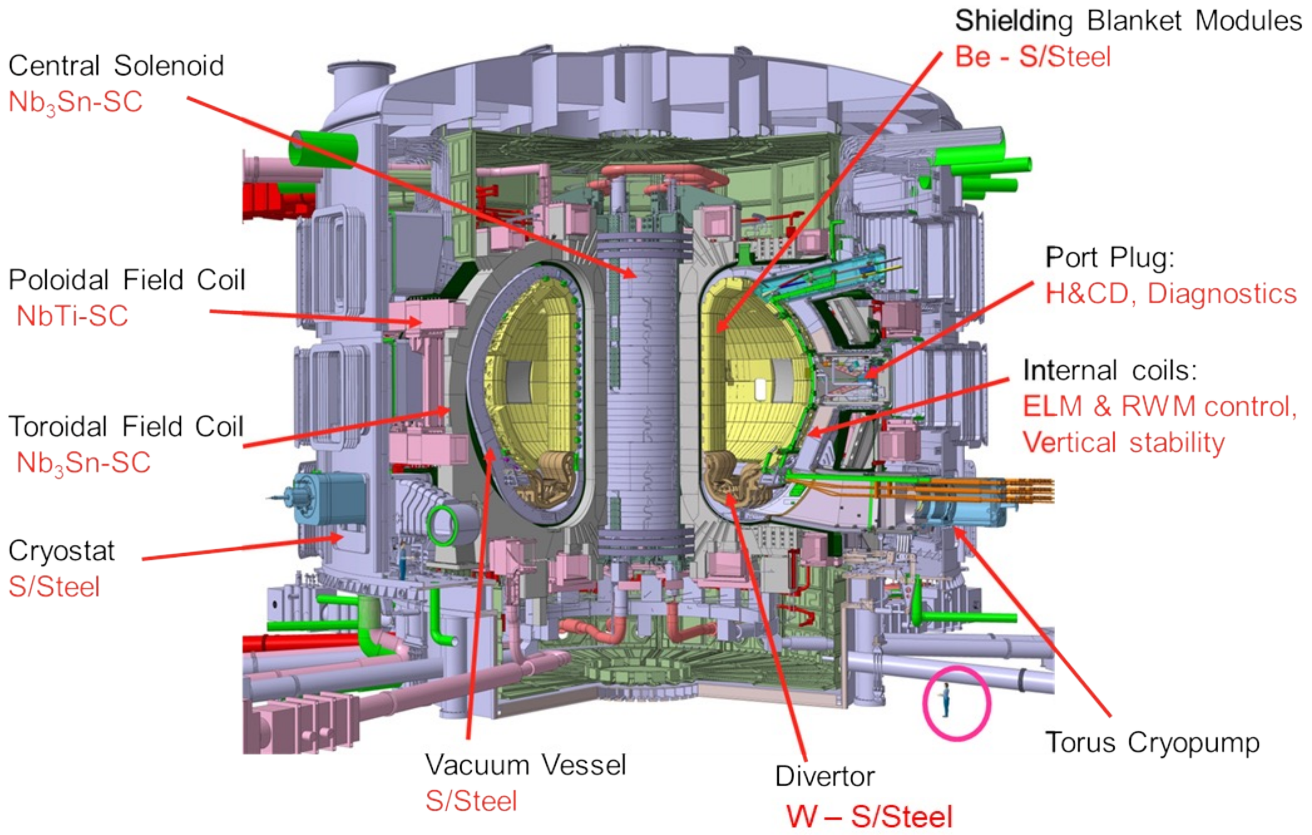
- MHD stable plasma operation + mitigation if global instabilities develop (disruptions)

M. Lehnen EPS 2017

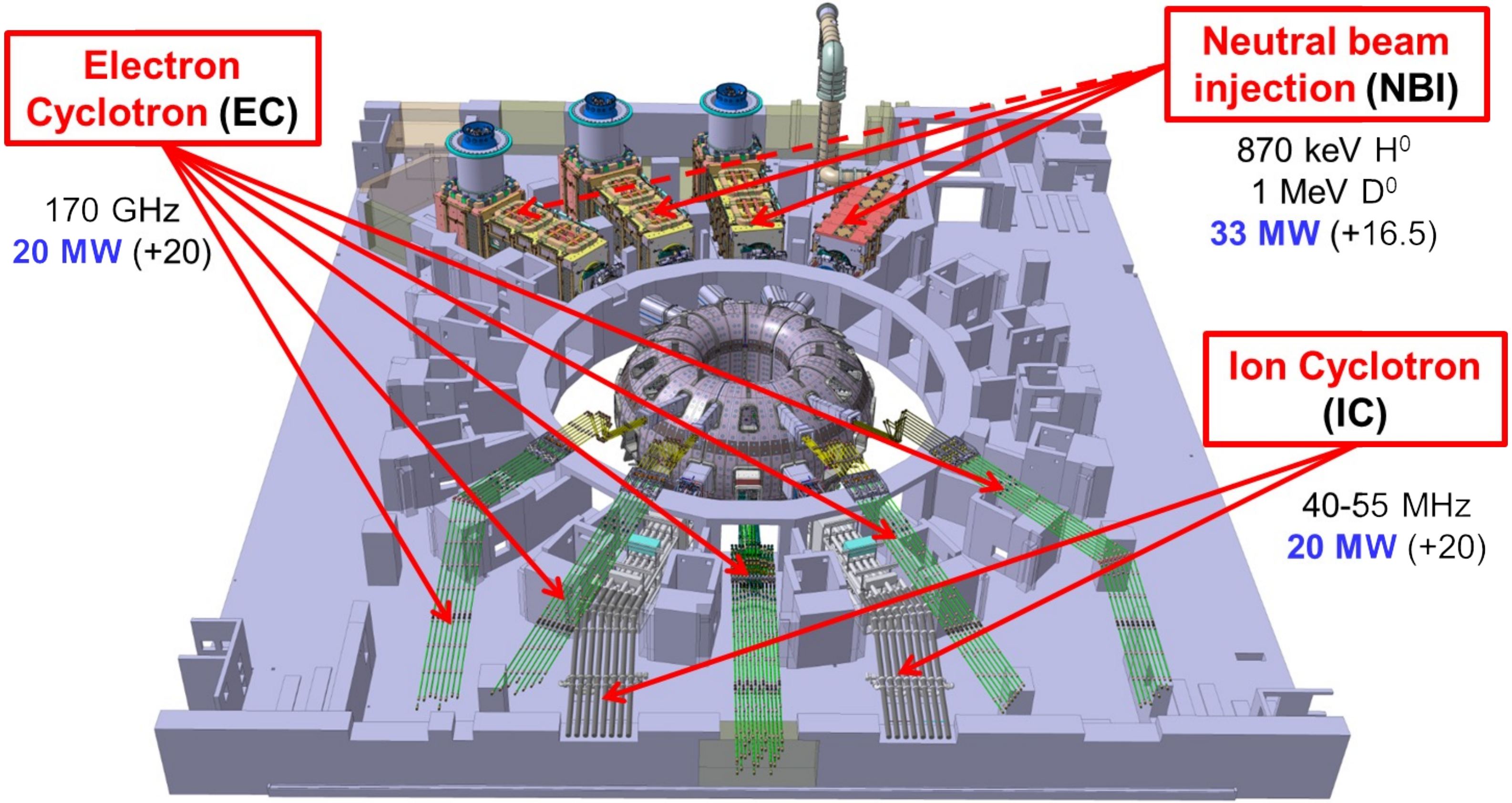




ITER Main Design Features



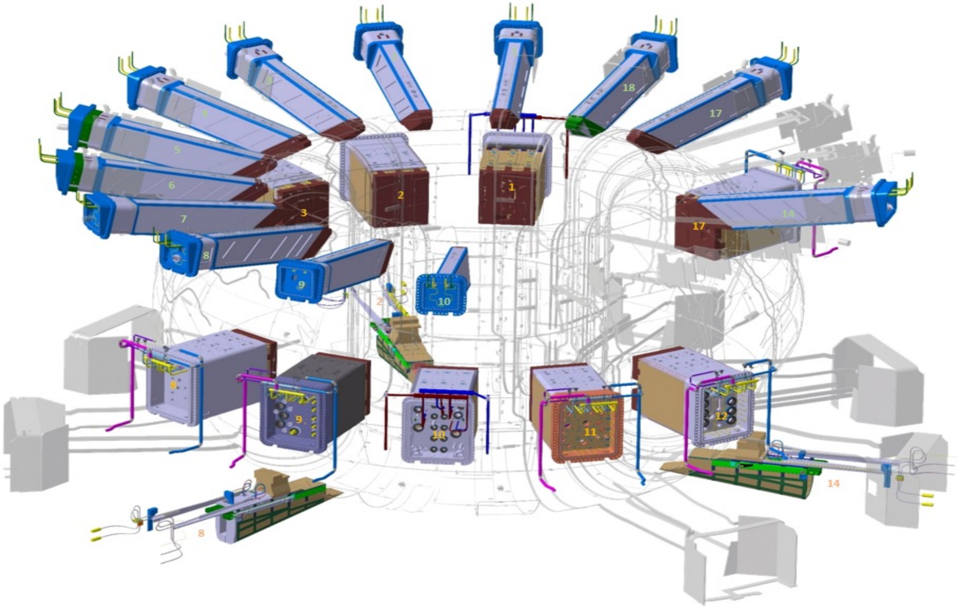
ITER Heating and Current Drive systems

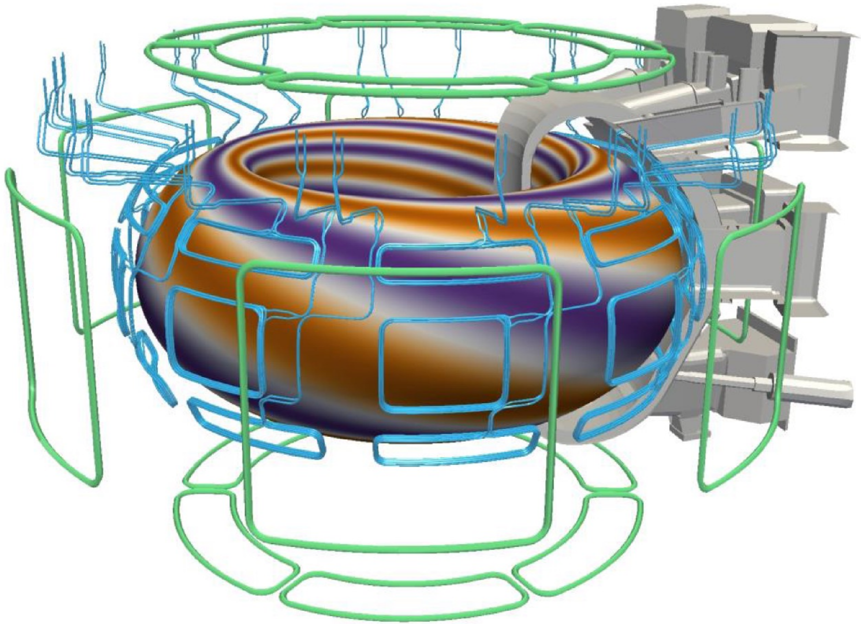


ITER Diagnostics and 3-D coils (Error Field, ELM control)

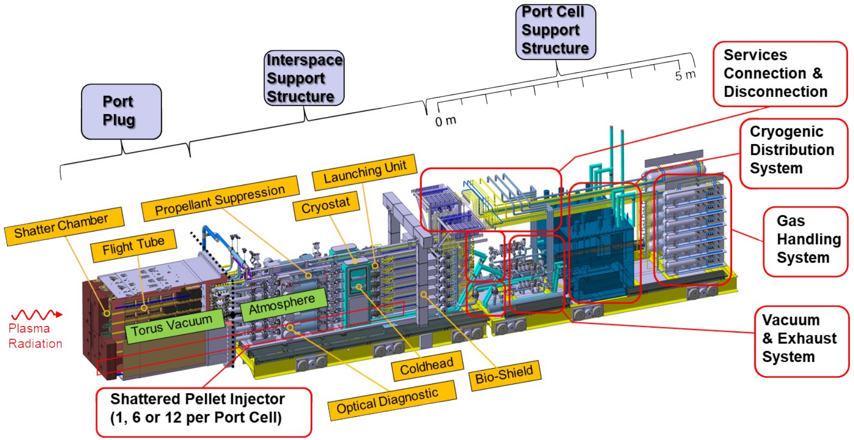
- ❑ Diagnostics: ~ 60 instruments measuring ~ 100 parameters

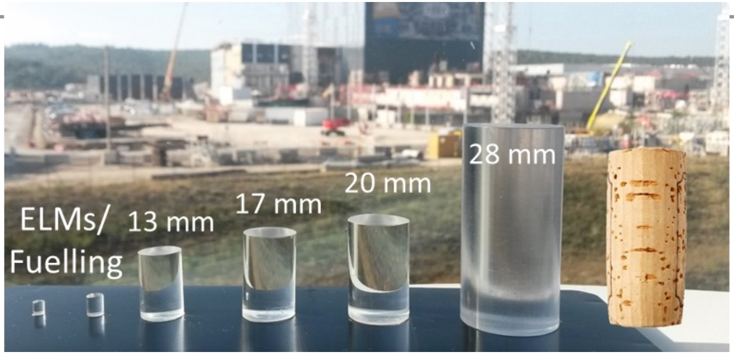
- ❑ External error field correction coils + internal ELM control coils

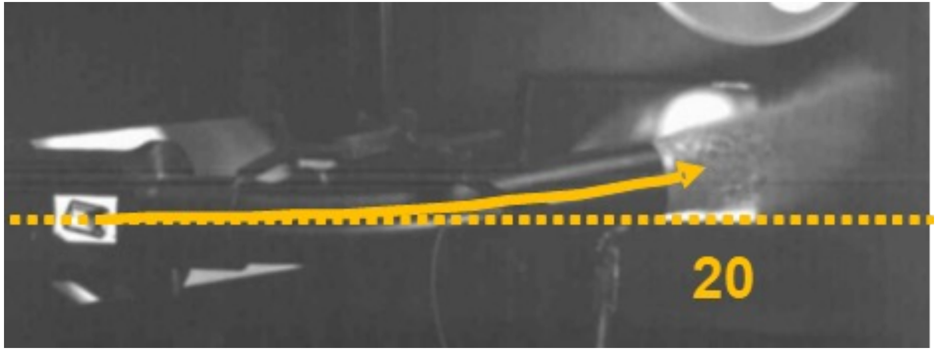


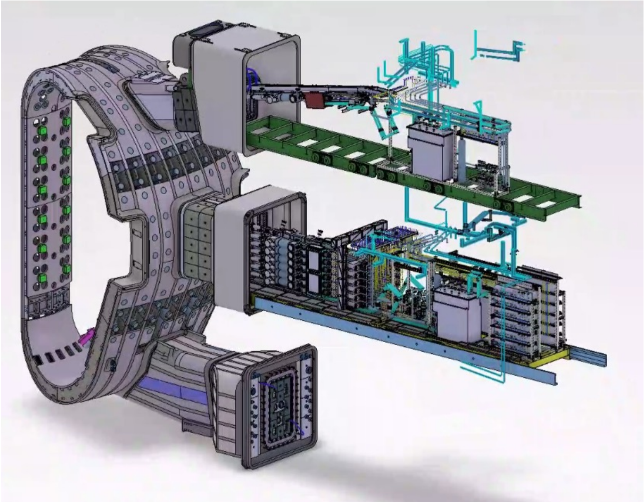


ITER Disruption Mitigation System



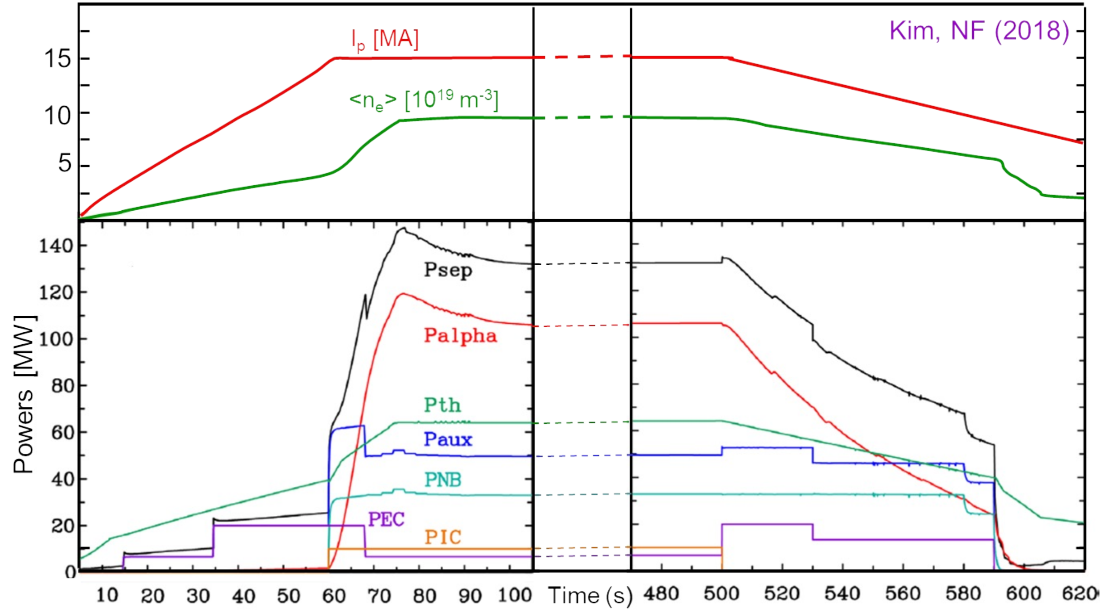


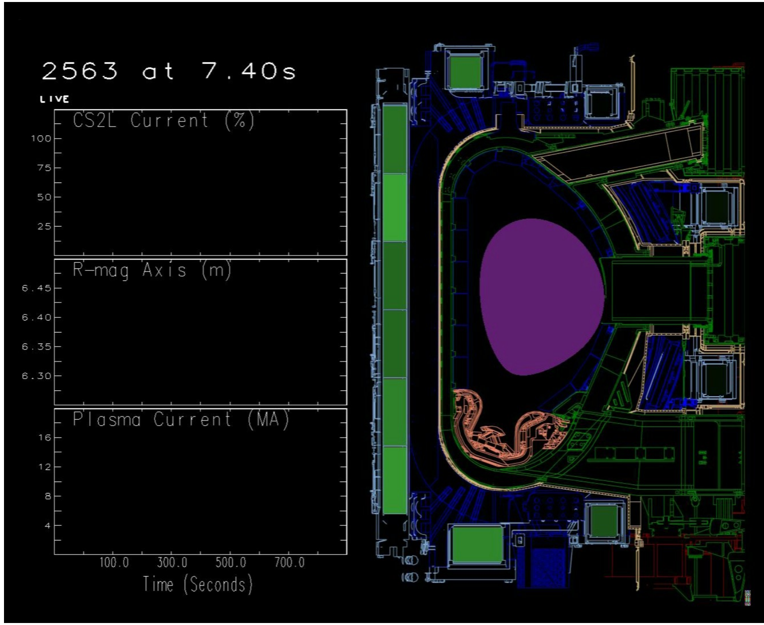




ITER Q = 10 scenario (300 – 500 s burn)

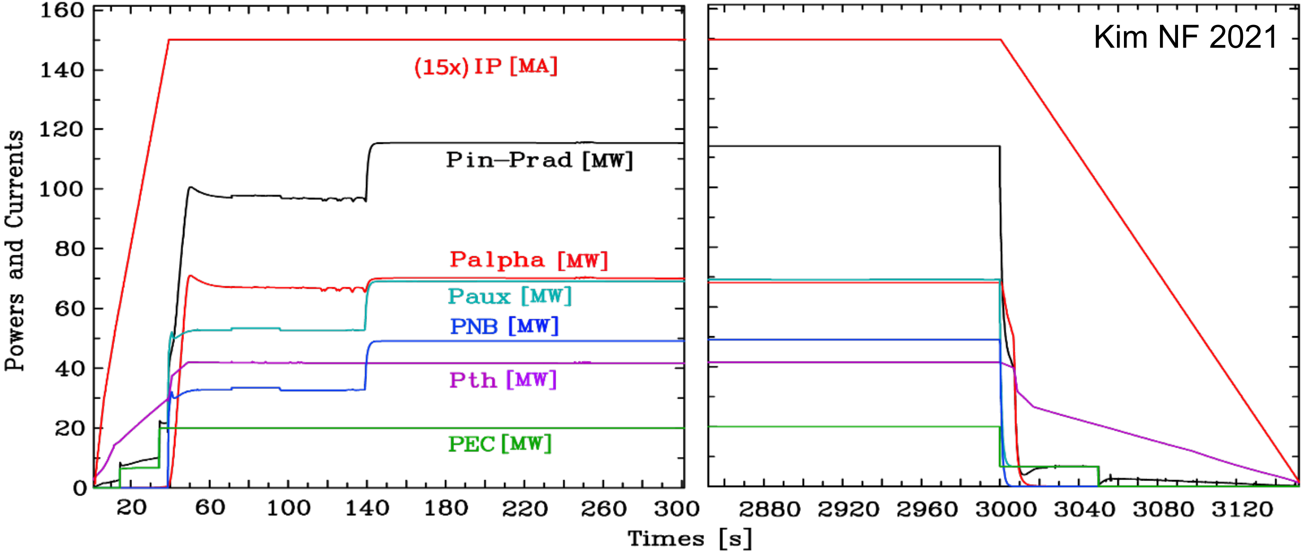
- Based on conventional sawtoothing H-mode with H_{98} = 1 → scenario used for the design of magnets and components (15 MA/5.3 T)
- $P_{aux} = P_{NBI} + P_{ECH}$ (+ P_{ICH}) ~ 50 MW → Alpha-heating dominant scenario with non-inductively driven current ~ 35%

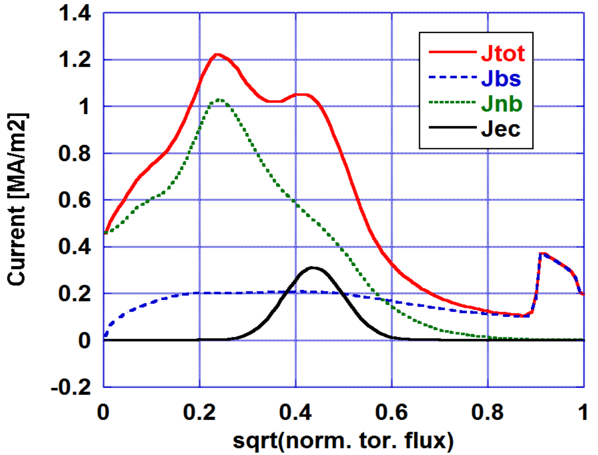




ITER Q ~ 5 scenario (steady-state)

- 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%





Polevoi NF 2020

ITER as a Project and overview of Construction Status

ITER

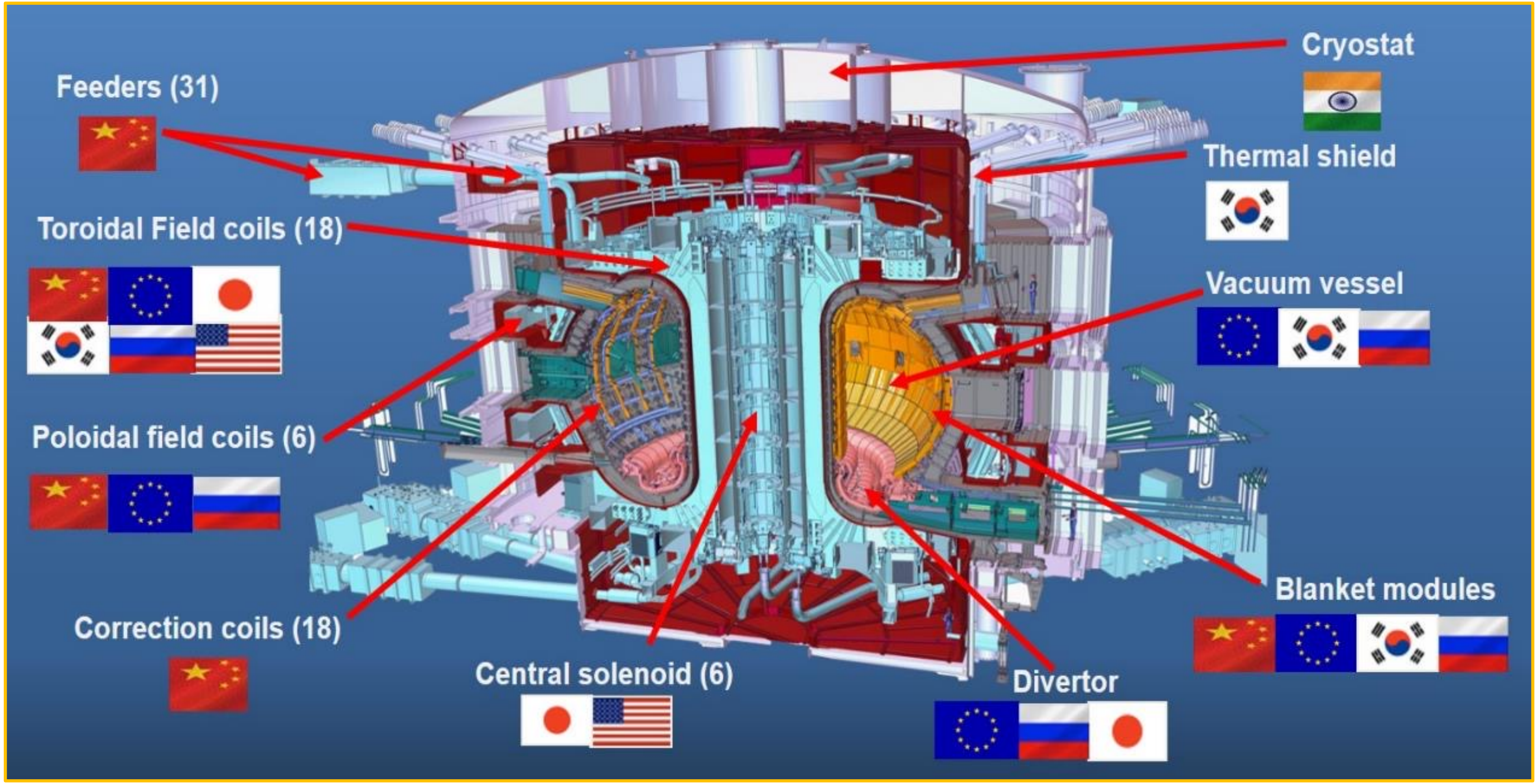
Global challenge, global response

- 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.

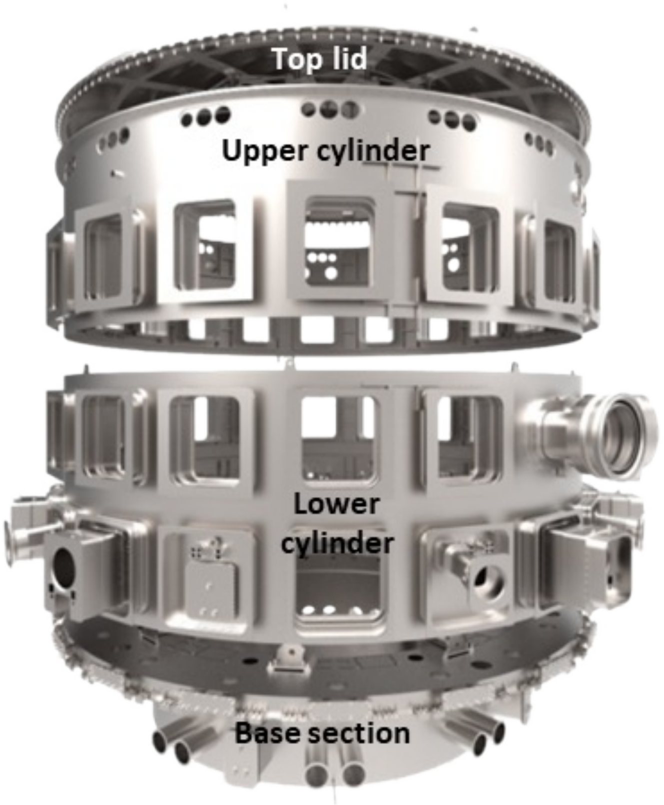
The seven ITER Members represent more than 50% of the world's population and about 85% of the global GDP

China EU India Japan Korea Russia USA

Construction ITER – Who manufactures What ?



ITER Cryostat

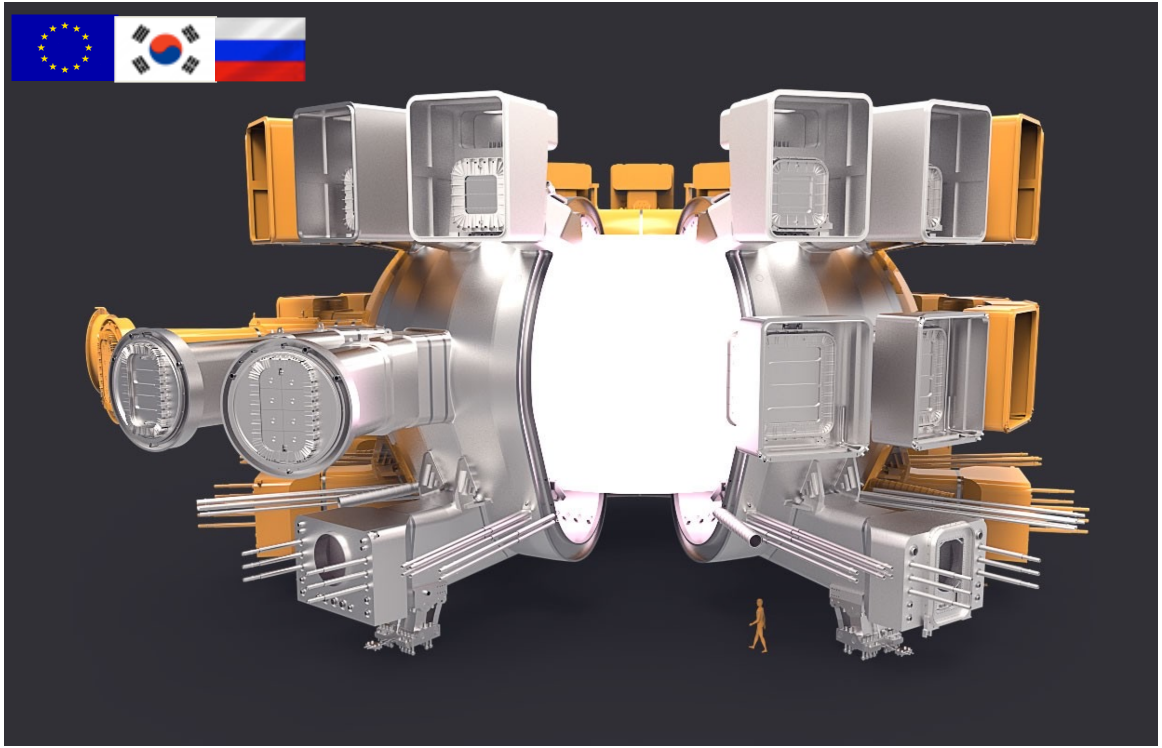


Largest stainless steel high-vacuum pressure container ever built

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

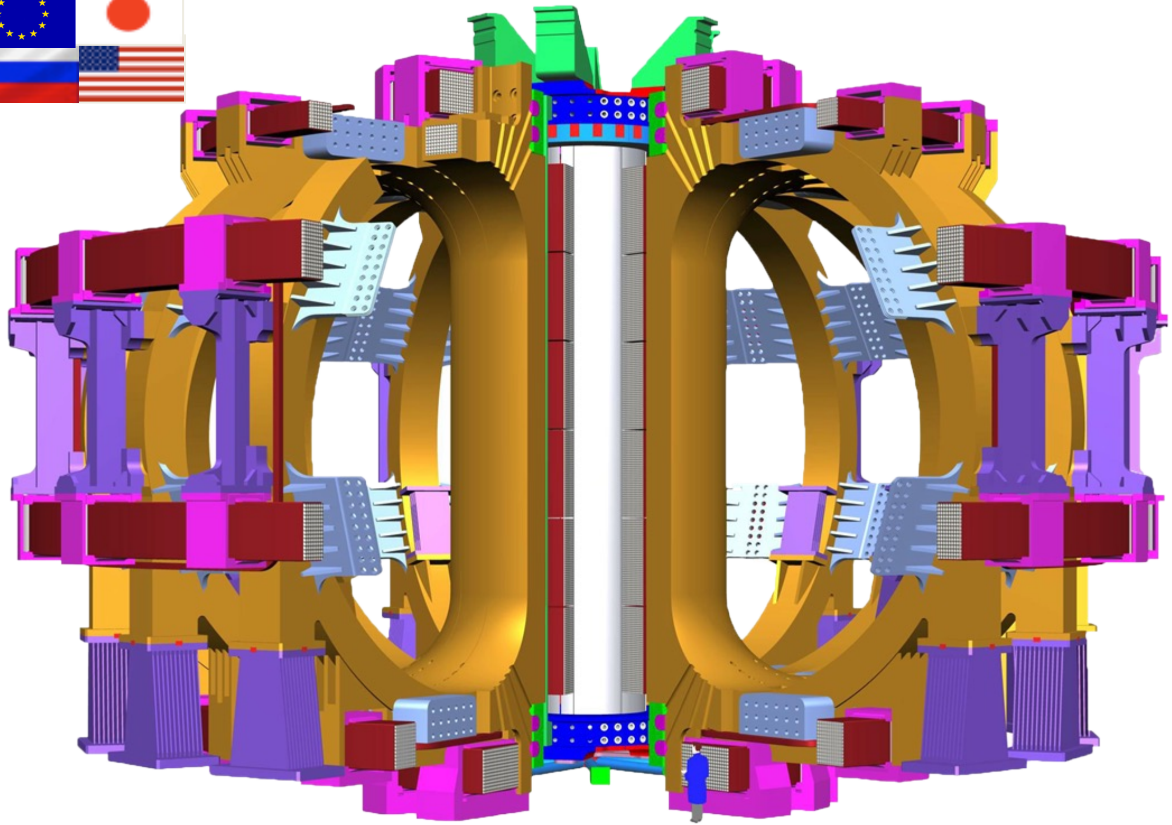
Primary containment barrier

Volume: 1,400 m^3

Plasma volume: 840 m^3

Weight: 8,500 t

ITER Magnet System

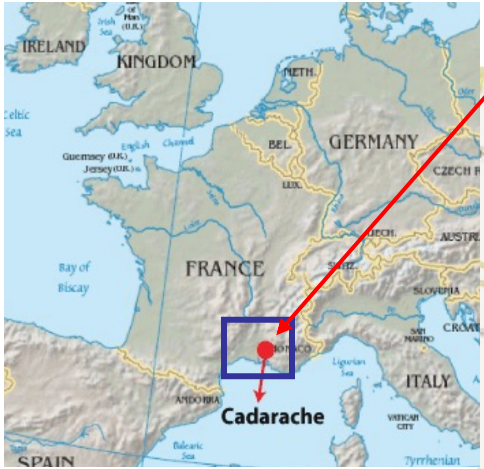


Central solenoid
- 13 m high
- 1,000 tons

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

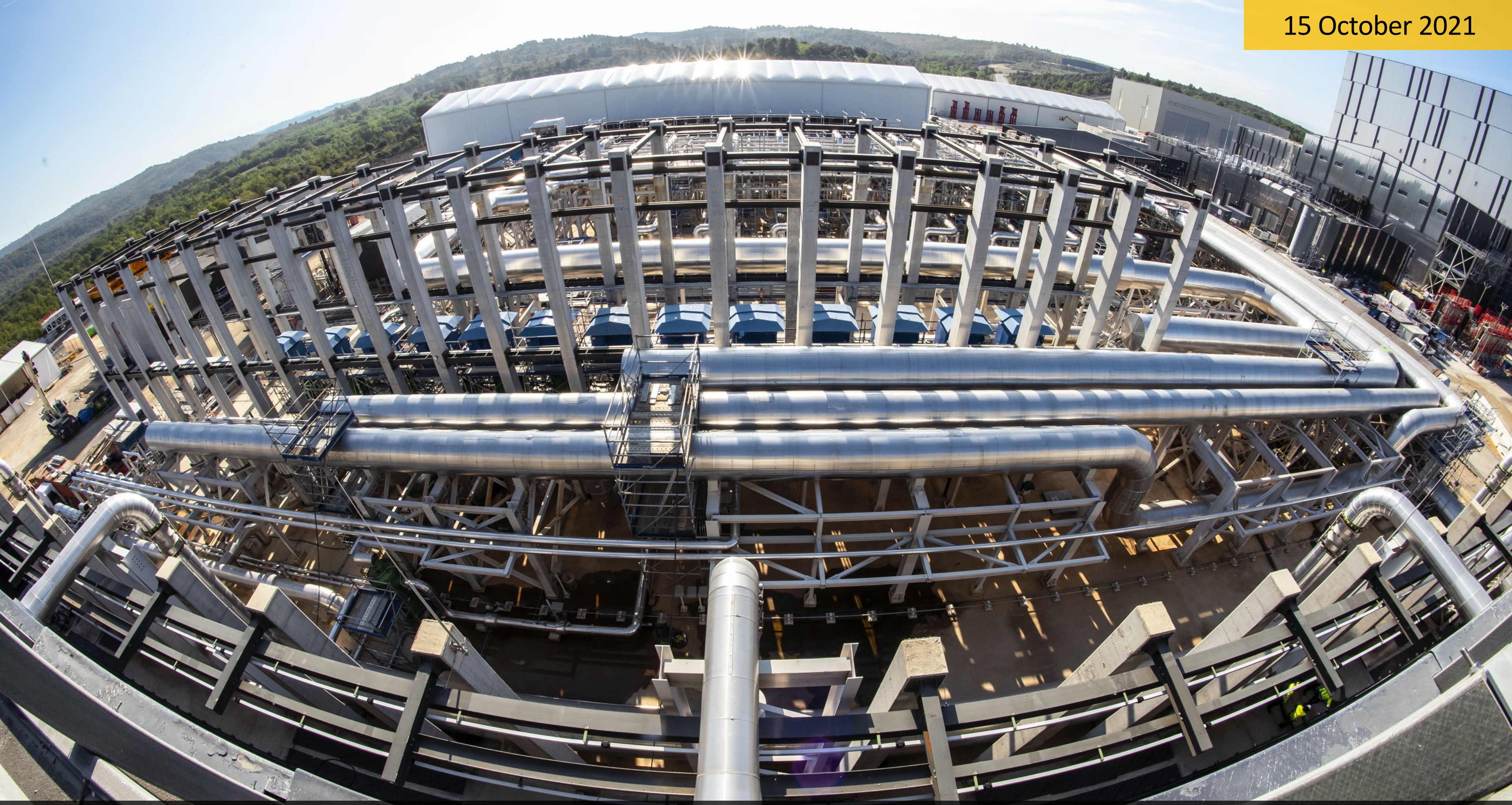
Many massive arrivals in 2020/22 (few shown)

ITER Site Construction Status

Progress in major areas (as of December 2021)

25 November 2021

Over 5000 t of equipment installed in the cryoplant in 3.5 years → 2 year commissioning period started



15 October 2021

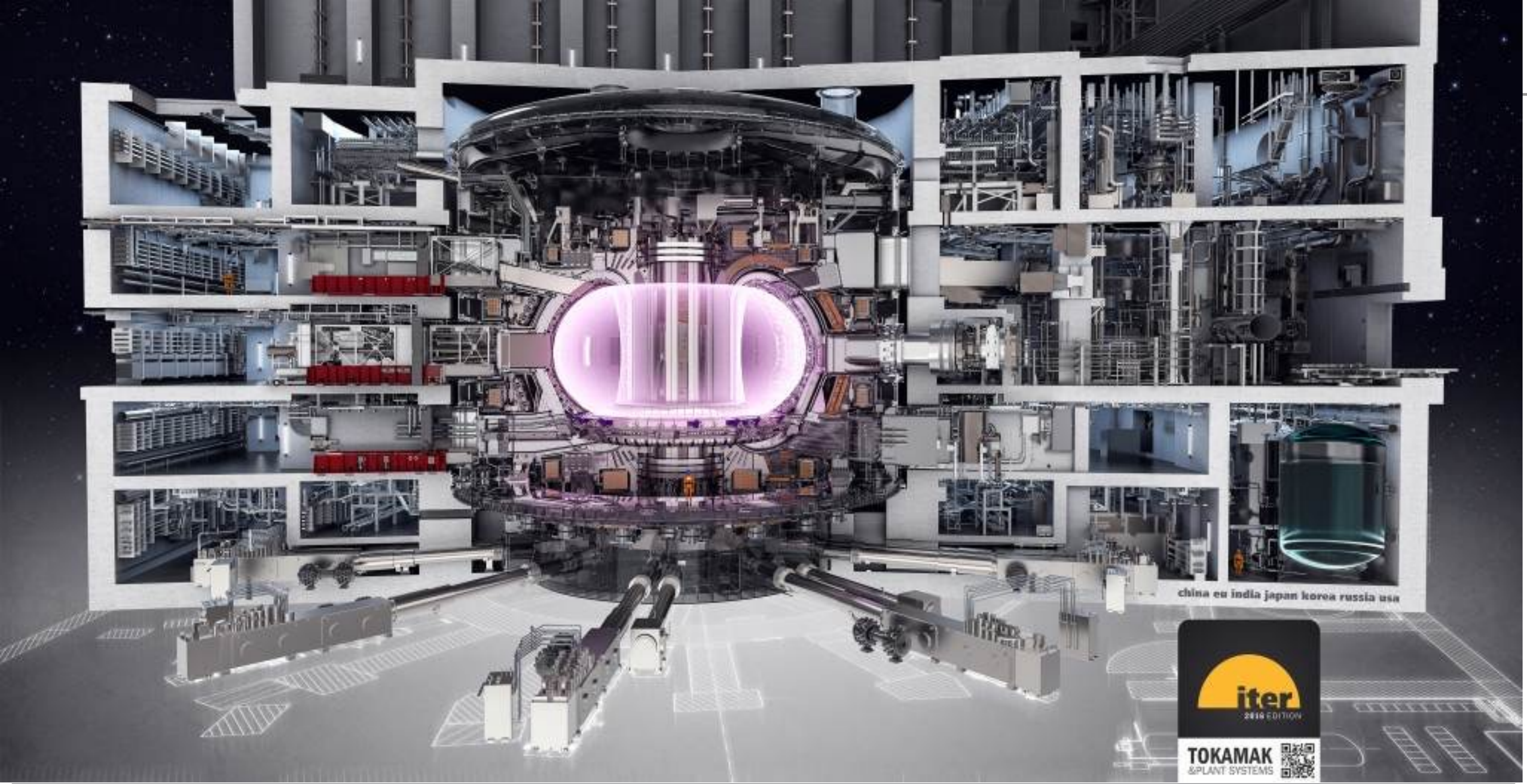
About 6000 t of equipment supplied by India for the cooling plant → plant commissioning now started

25 March 2021

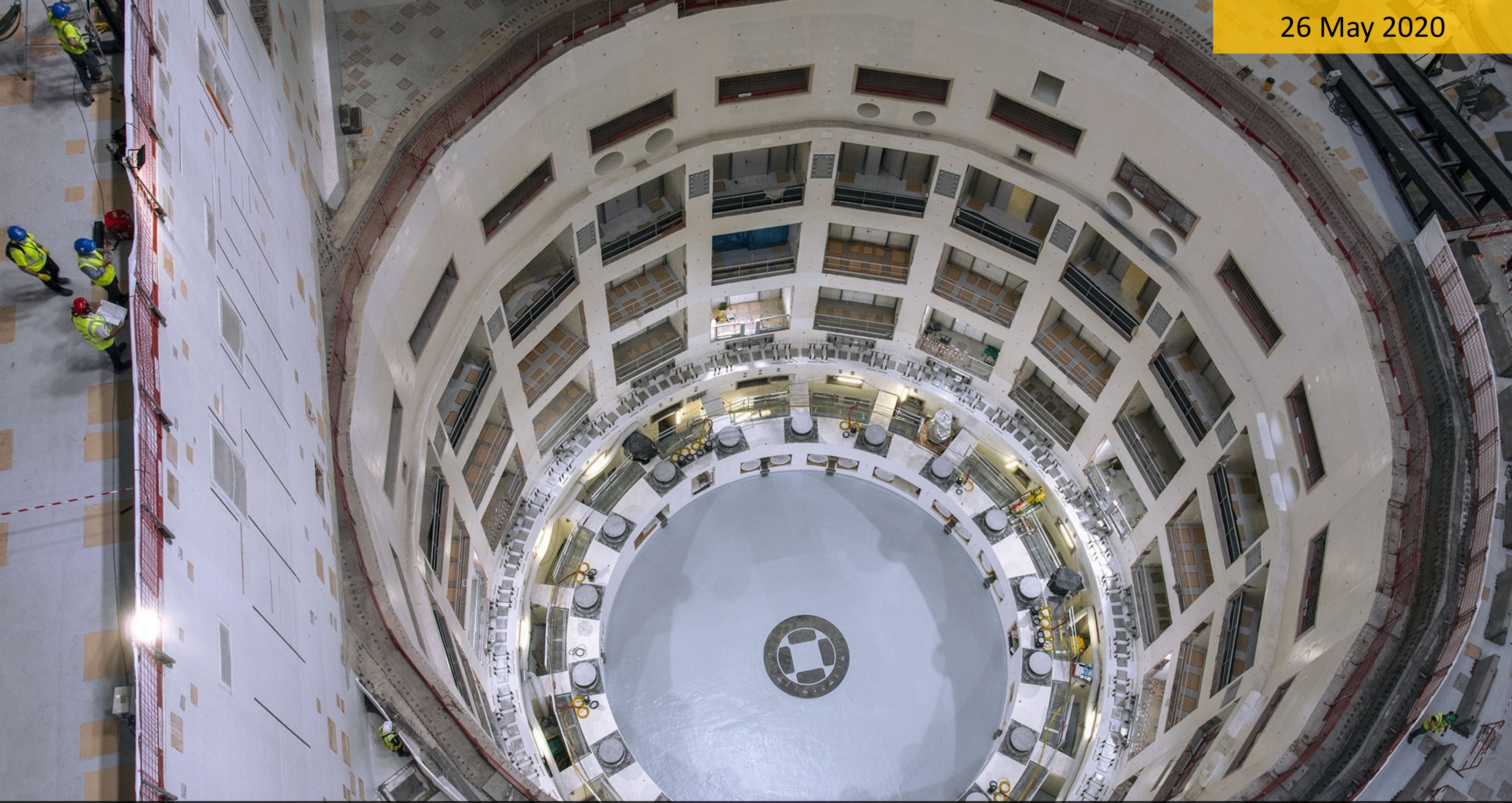
Magnet conversion buildings filling up with DC busbars for superconducting coils

8 December 2021

ITER Tokamak Construction Status

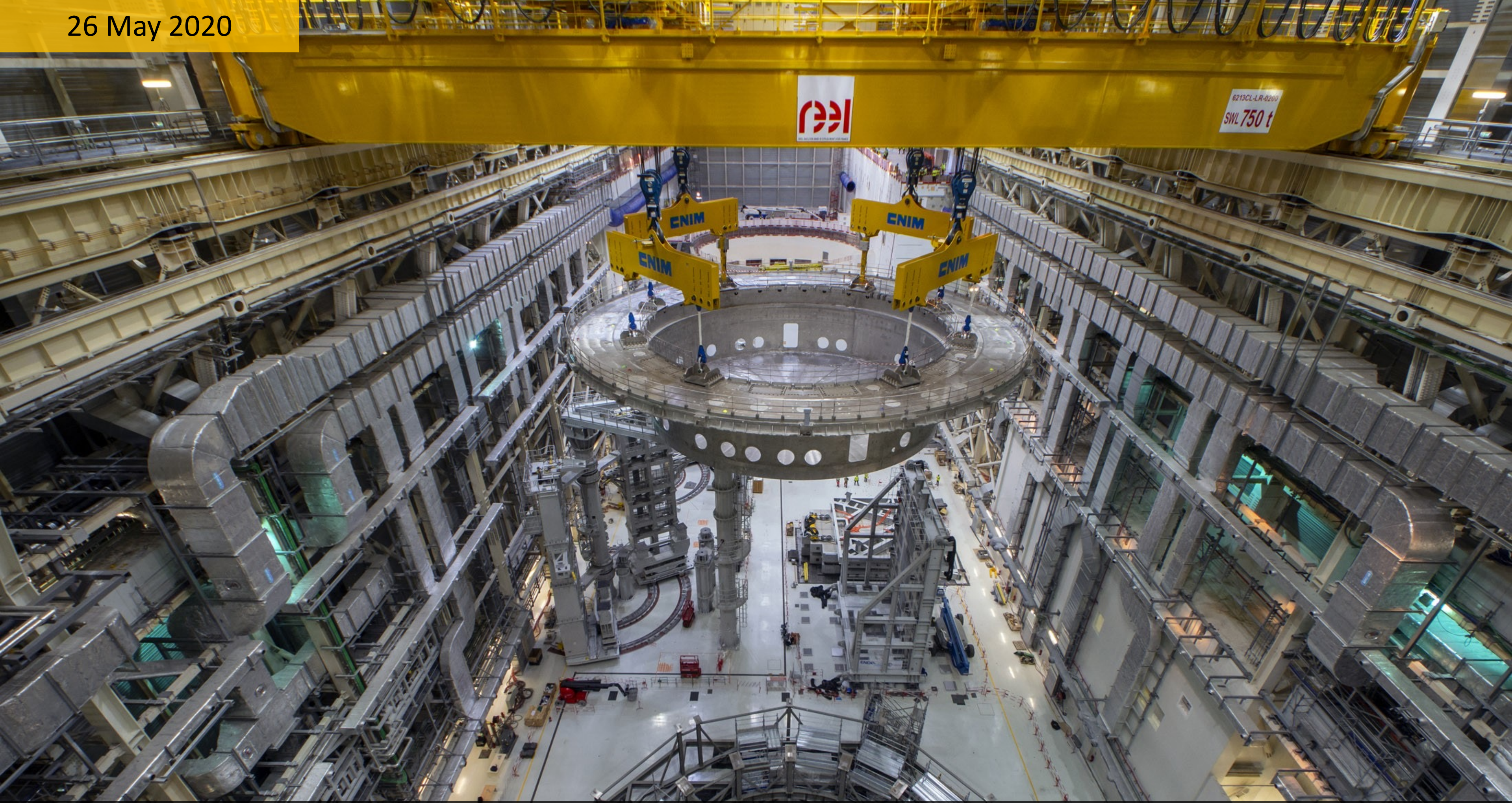

china eu india japan korea russia usa
iter
2016 EDITION
TOKAMAK
&PLANT SYSTEMS

26 May 2020



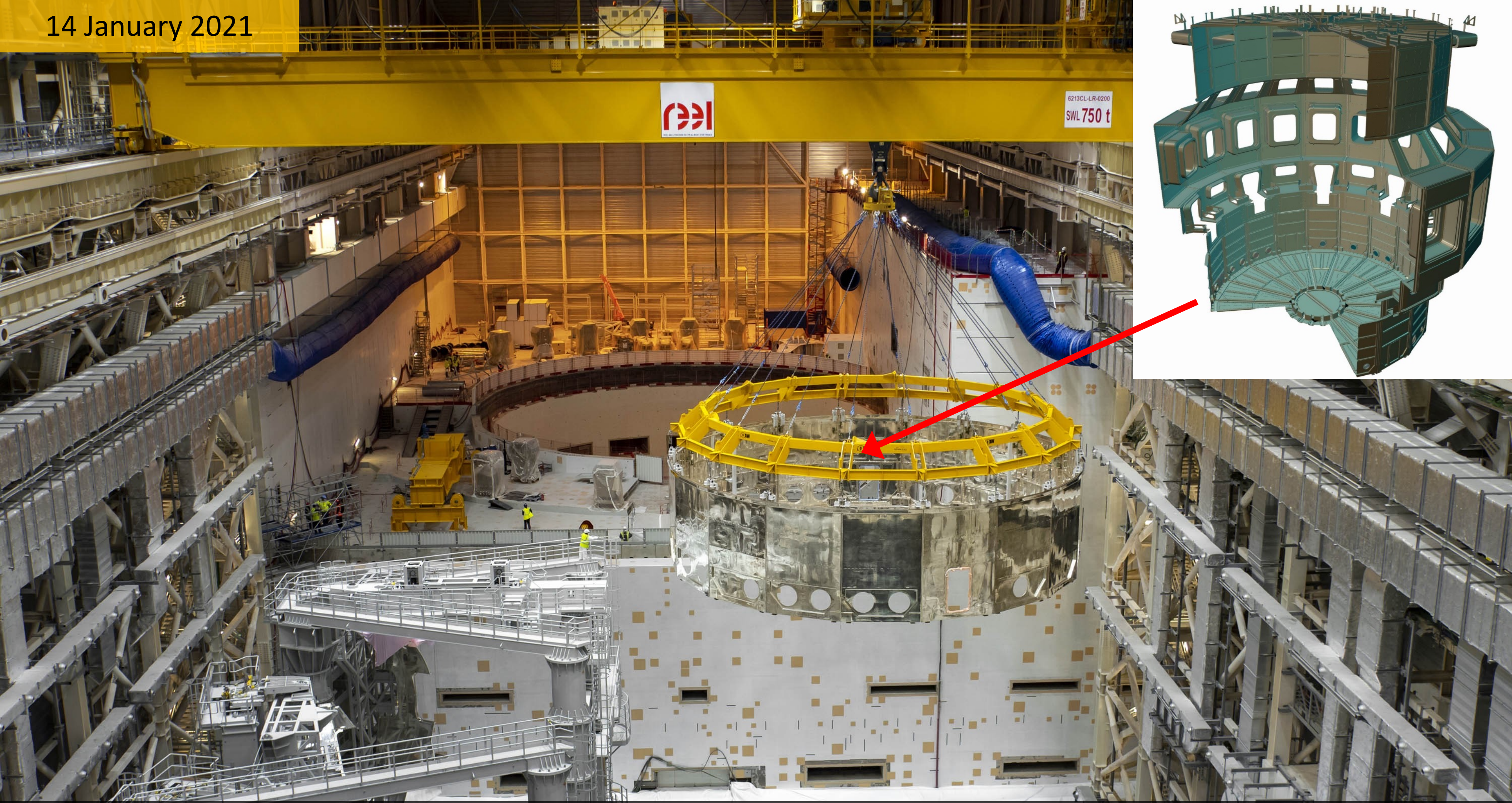
Temporary bioshield lid removed: Tokamak Pit painted up and ready for first major components

26 May 2020



The big lift: 1250 tonne, 30 m diameter cryostat base on its way to the pit

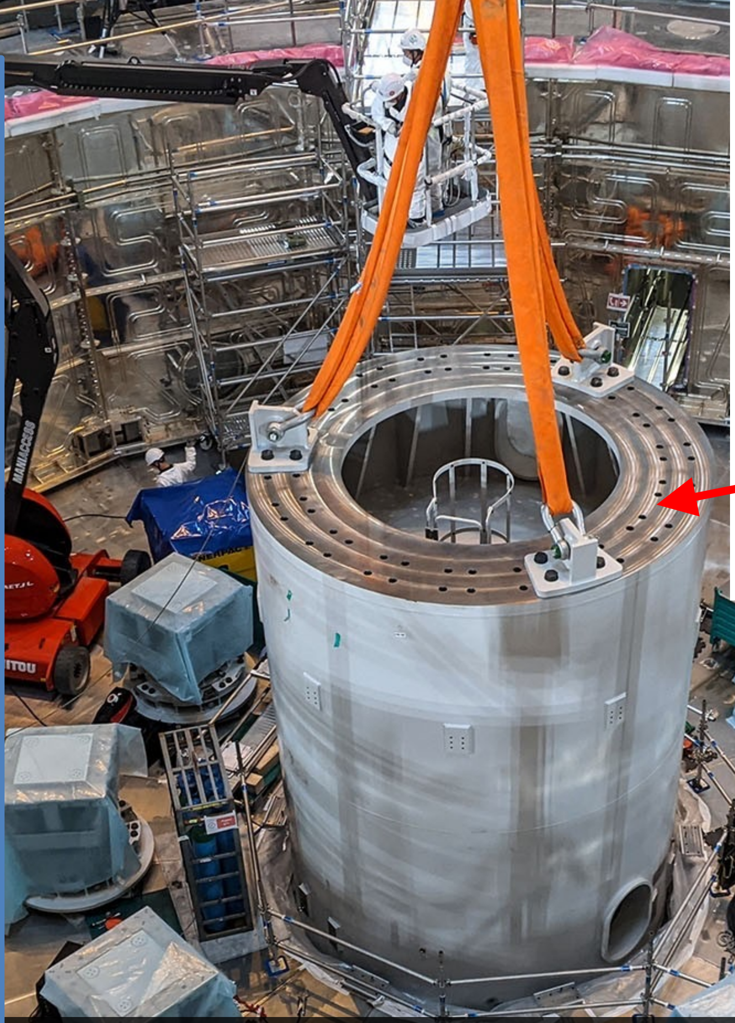
14 January 2021

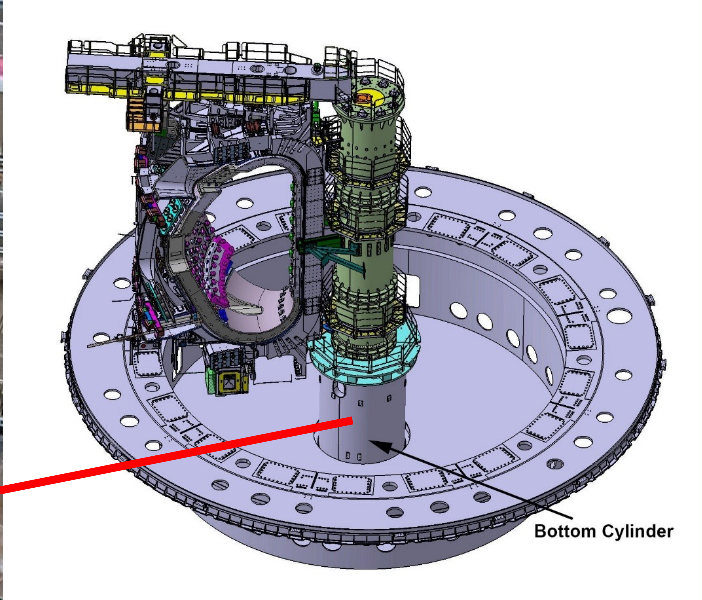


Lower cylinder thermal shield on its way

27 March 2021

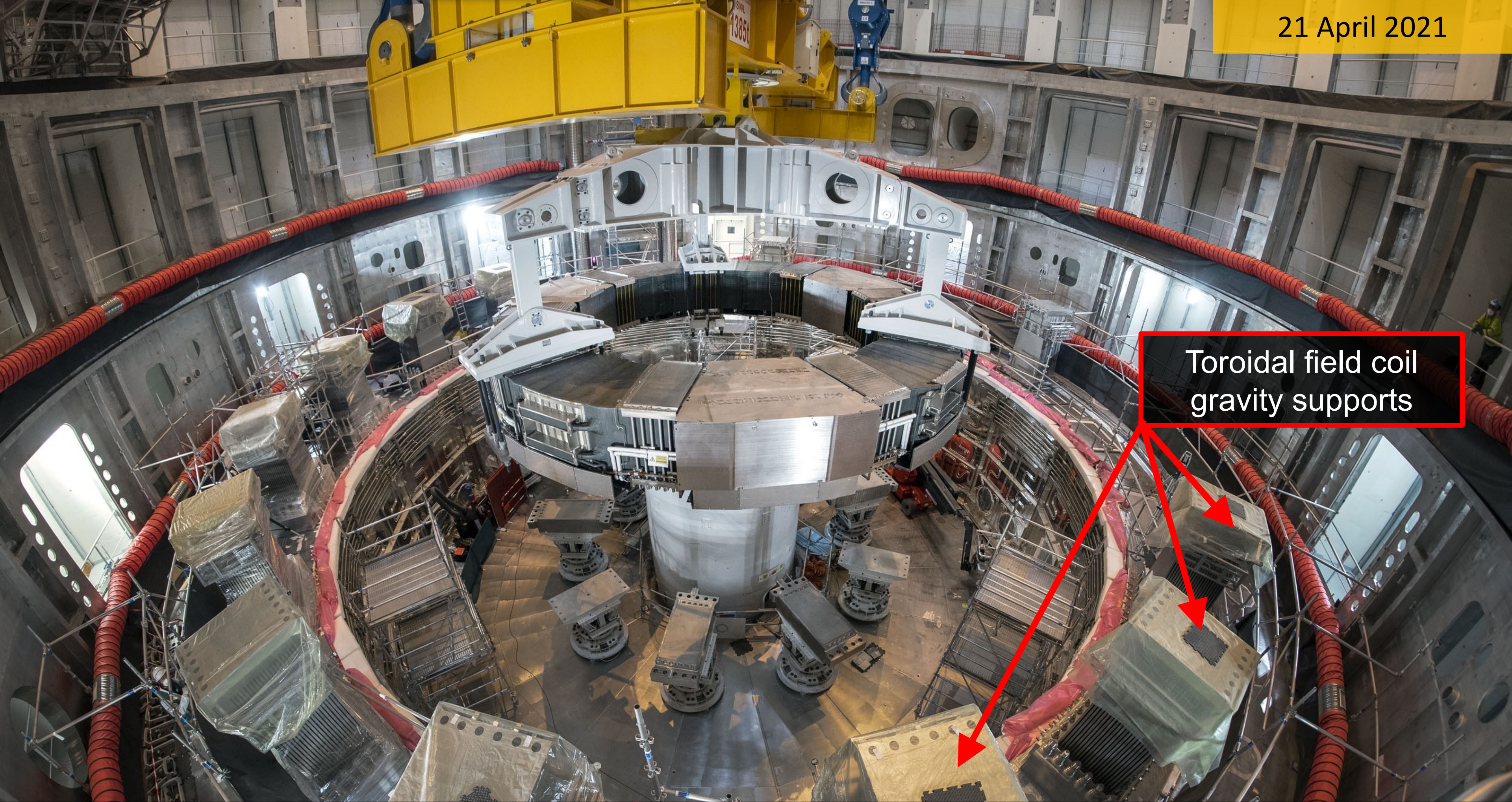
Full assembly





Lower cylinder of in-pit Assembly Tool

21 April 2021

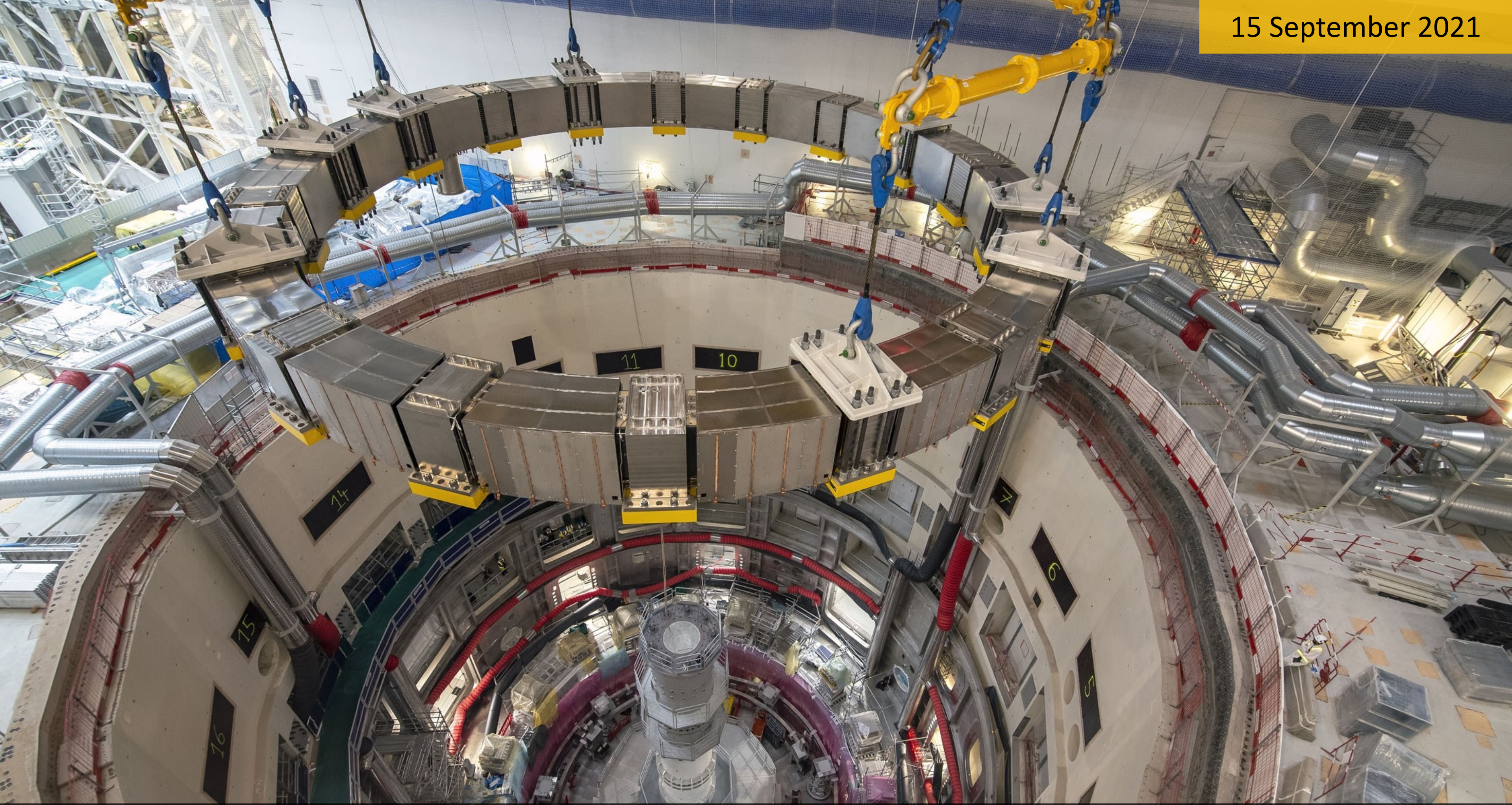


First poloidal field coil PF6 inserted onto temporary supports

7 September 2021

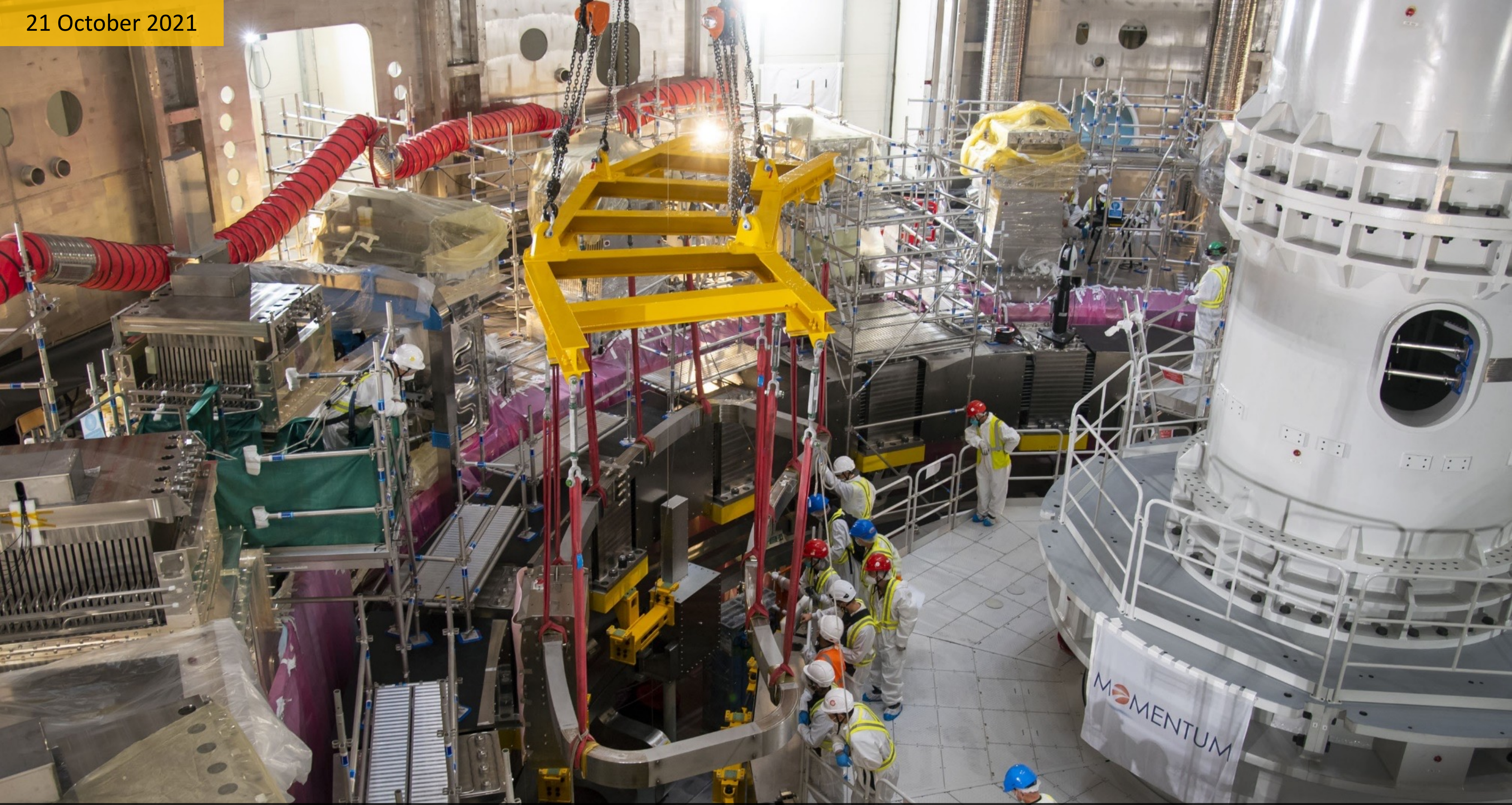
Radial beam testing → beams carry each VV sector and must be very precisely positioned

15 September 2021



PF 5 coil lifted into the tokamak pit

21 October 2021

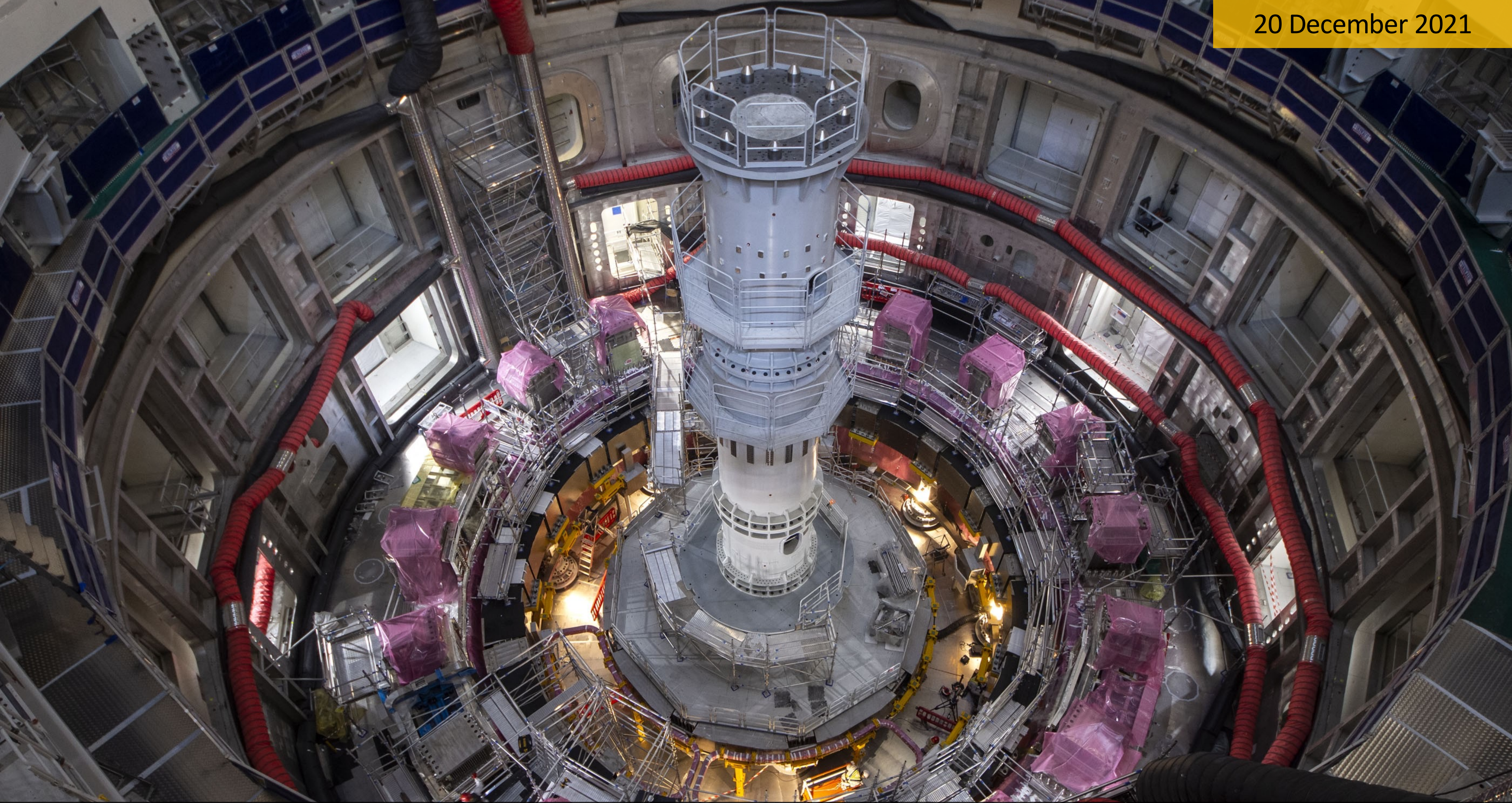


Installation of one of the lower (bottom) correction coils (BCC)

8 December 2021

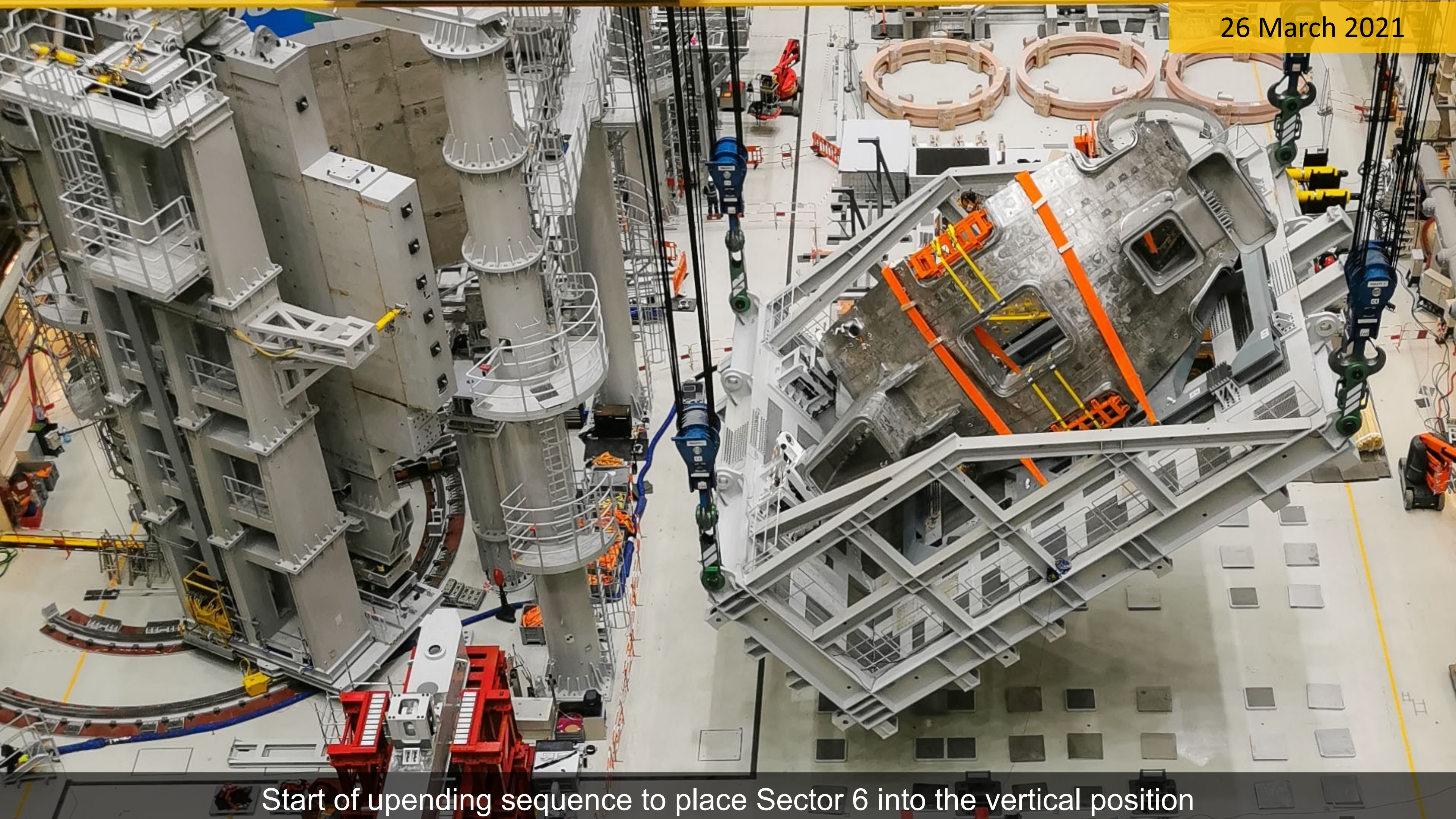
Metrology and adjustment

20 December 2021



Tokamak Pit ready for 1st VV sector

26 March 2021



Start of upending sequence to place Sector 6 into the vertical position

6 April 2021

Final step: transfer to the SSAT

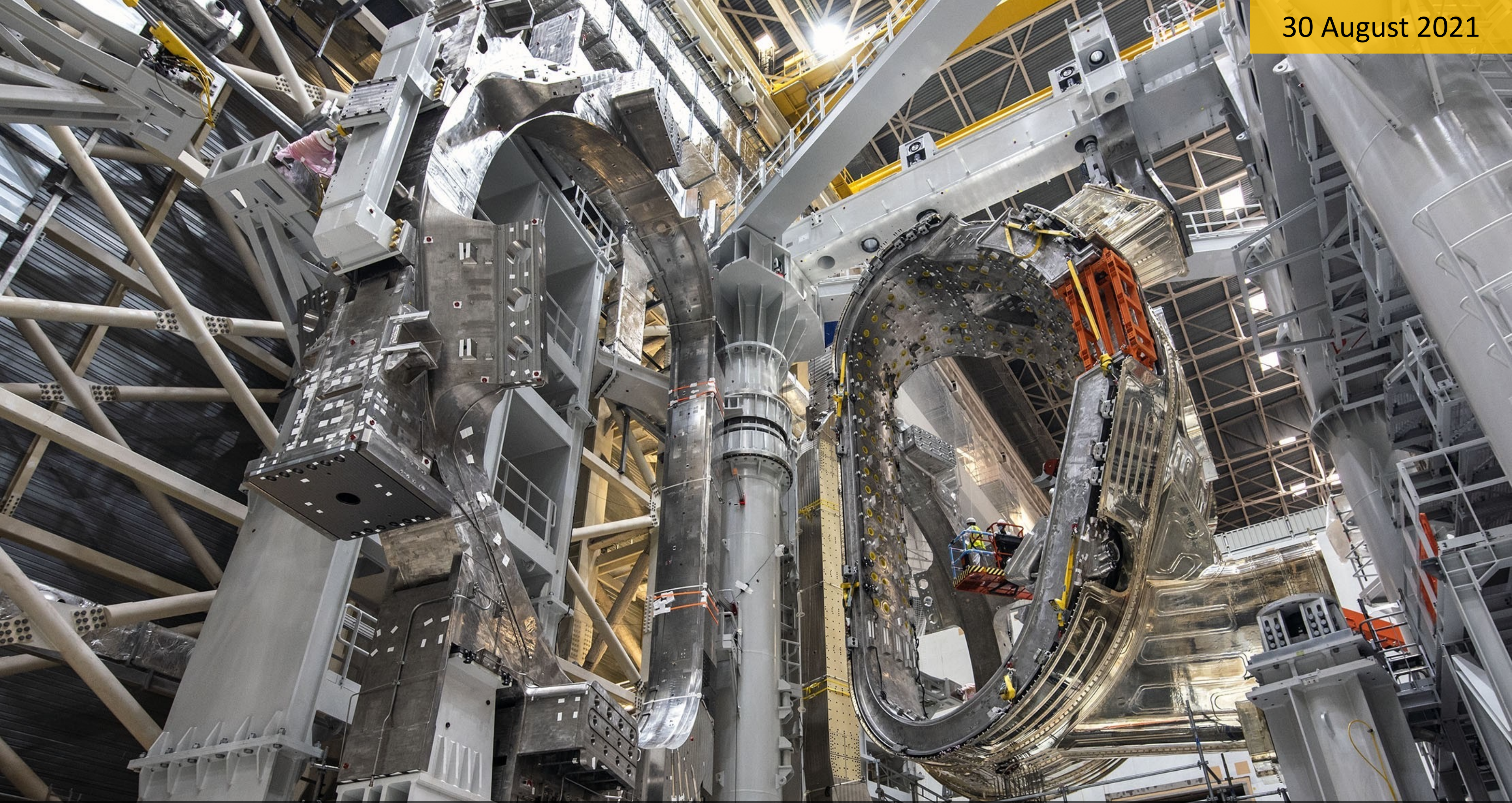
6 April 2021

And finally, inserted from above into the SSAT

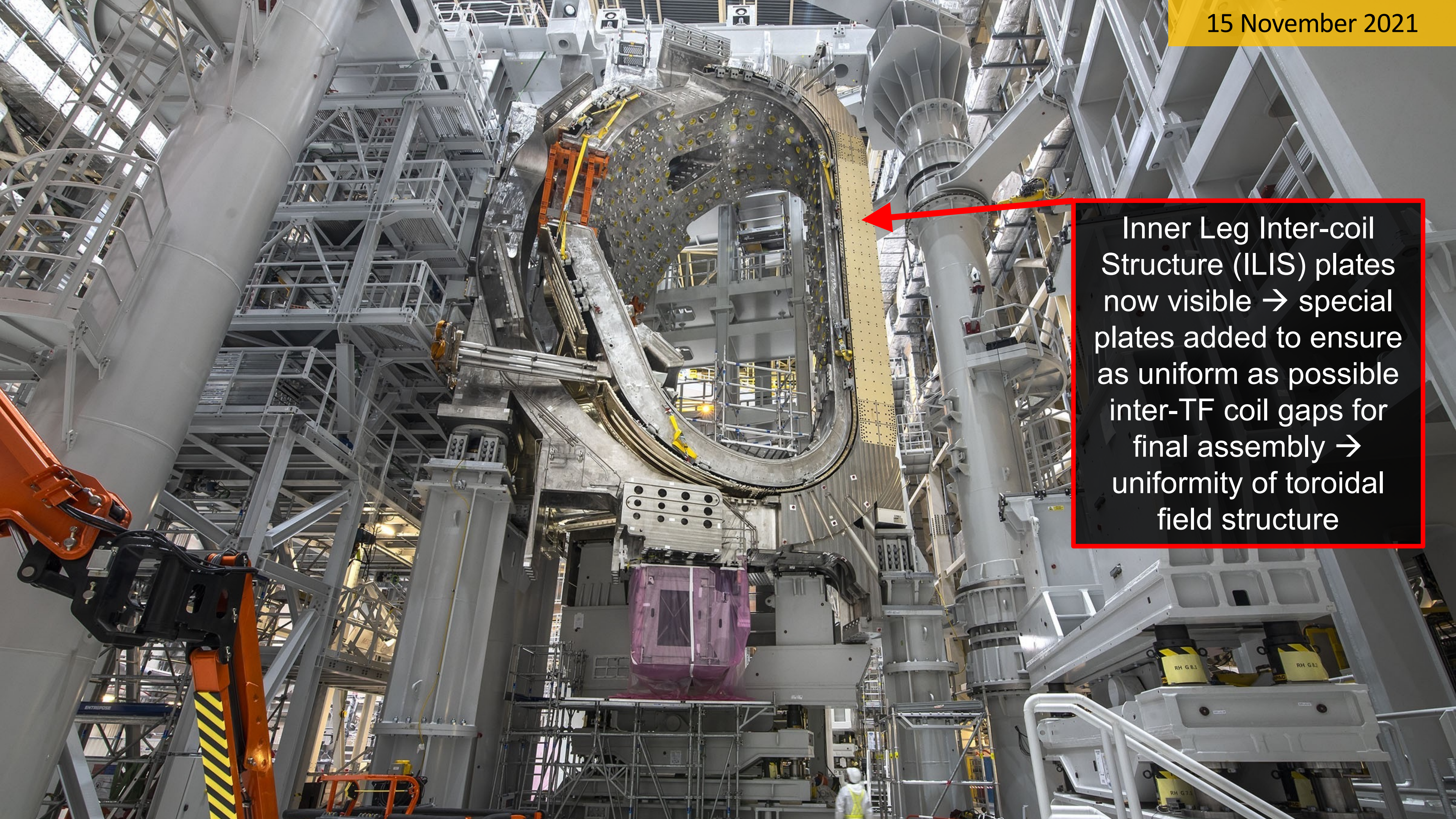
21 June 2021

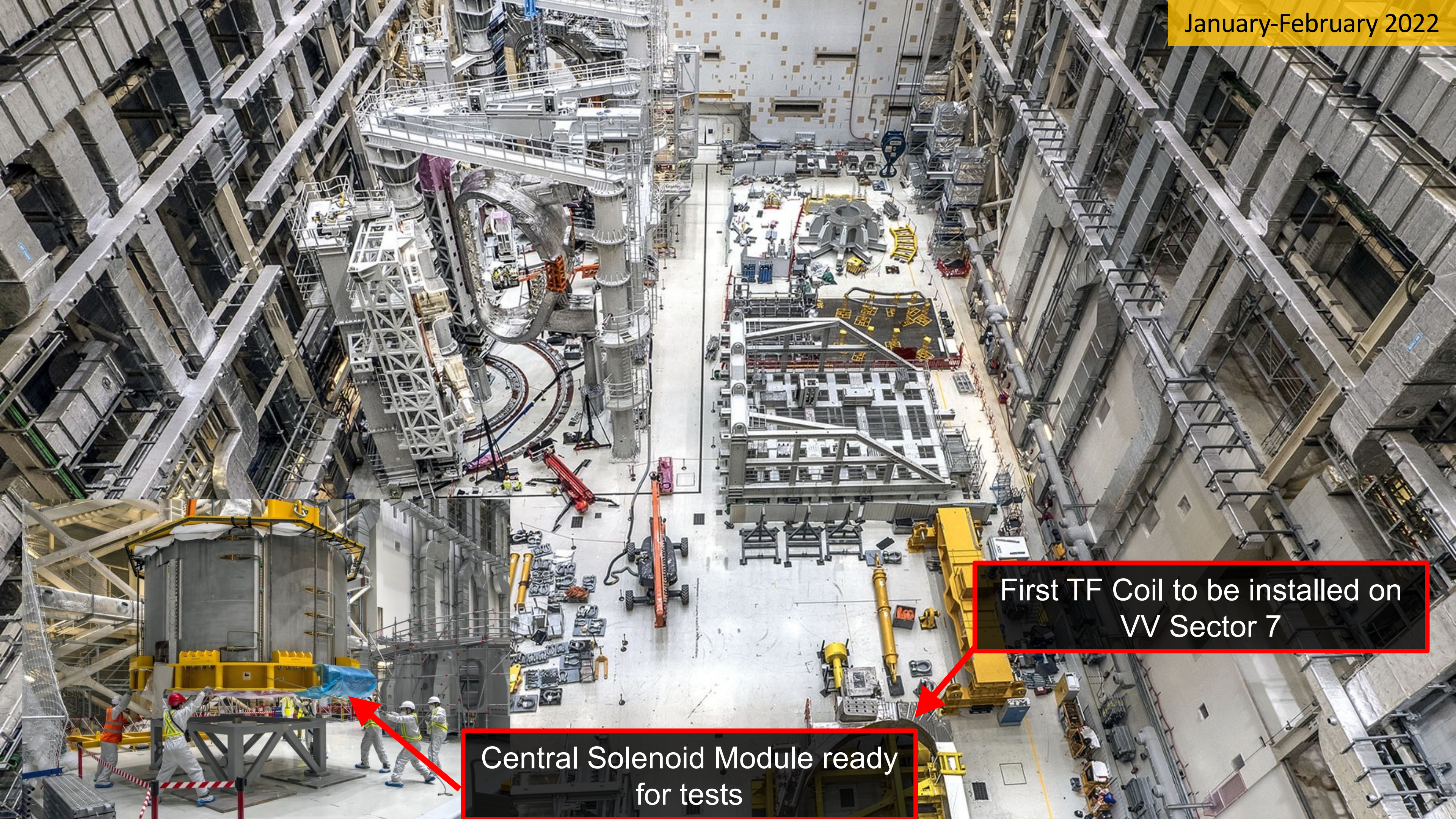
Inboard thermal shield section clamped to VV Sector #6

30 August 2021



Just prior to final positioning of TF coils


15 November 2021
Inner Leg Inter-coil Structure (ILIS) plates now visible → special plates added to ensure as uniform as possible inter-TF coil gaps for final assembly → uniformity of toroidal field structure

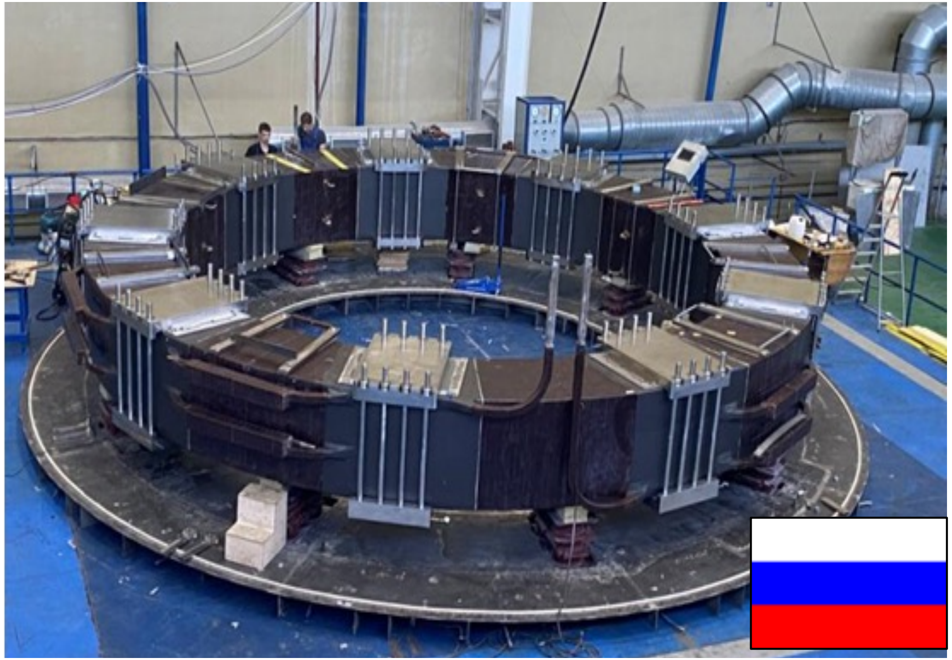

January-February 2022
First TF Coil to be installed on VV Sector 7
Central Solenoid Module ready for tests

Manufacturing progress: on-going globally- I

JA: 9 coils
3 coils delivered to IO (TF 12,13 already on VV Sector 6), 2 more en-route
2 coils in WP integration, 2 coils WP impregnation

EU: 10 coils
6 coils delivered to IO
3 coils in final stages
Last coil in WP cold test

Clamps, closing plates, cryogenic strapping and diagnostic systems installed → delivery to IO early 2022



Manufacturing progress: on-going globally- II

KO:
Sectors 6,7 at IO, Sector 8 just arrived
Sector 1 in final stage of manufacture

EU: as of October 2021
Sector 5: 95%. Sector 4: 91%
Sector 9: 80%, Sector 3: 74%,
Sector 2: 74%

Sector 8: being loaded onto its transport platform

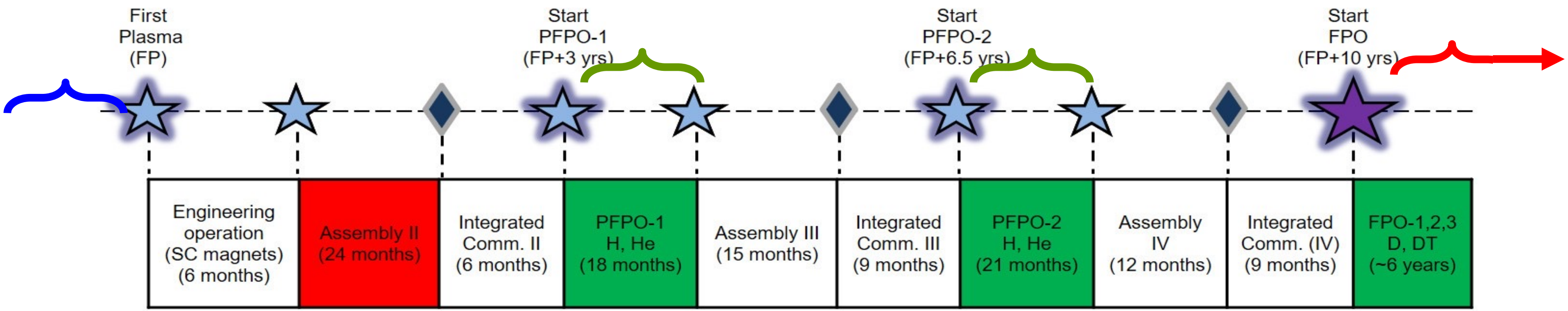
Sector 5: after inner shell welding

Russia completed Full Scale Prototype of the divertor dome: arrived at ITER on 14 December 2021

Overview of ITER Research Plan (IRP) and staged approach

ITER Research Plan (IRP)

- R&D Strategy to achieve project's goals with distinct phases :
  - Integrated Commissioning, First Plasma, Engineering Operation
  - Pre-Fusion Operation phase (H/He)
  - Fusion Power Operation (D and DT) → Achievement of high Q goals



ITER Research Plan and Supporting R&D

- ITER Research Plan made publicly available in 2018 (available as Technical Report (ITR-18-003) → now ITER baseline document
- R&D topics to support effective execution of Research Plan made accessible to fusion community (ITR-20-008) → used to focus R&D programmes (e.g. ITPA)

Conclusions

- ITER will demonstrate the scientific and technological feasibility of fusion power as energy source for humankind
- ITER construction is progressing well despite challenges posed by covid pandemic → 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 is moving forward towards First Plasma!