Status of ITER: the world's largest fusion experiment

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ICTP-IAEA Fusion Energy School, Trieste, Italy, 20 May 2026

IDM UID: FKVY3D

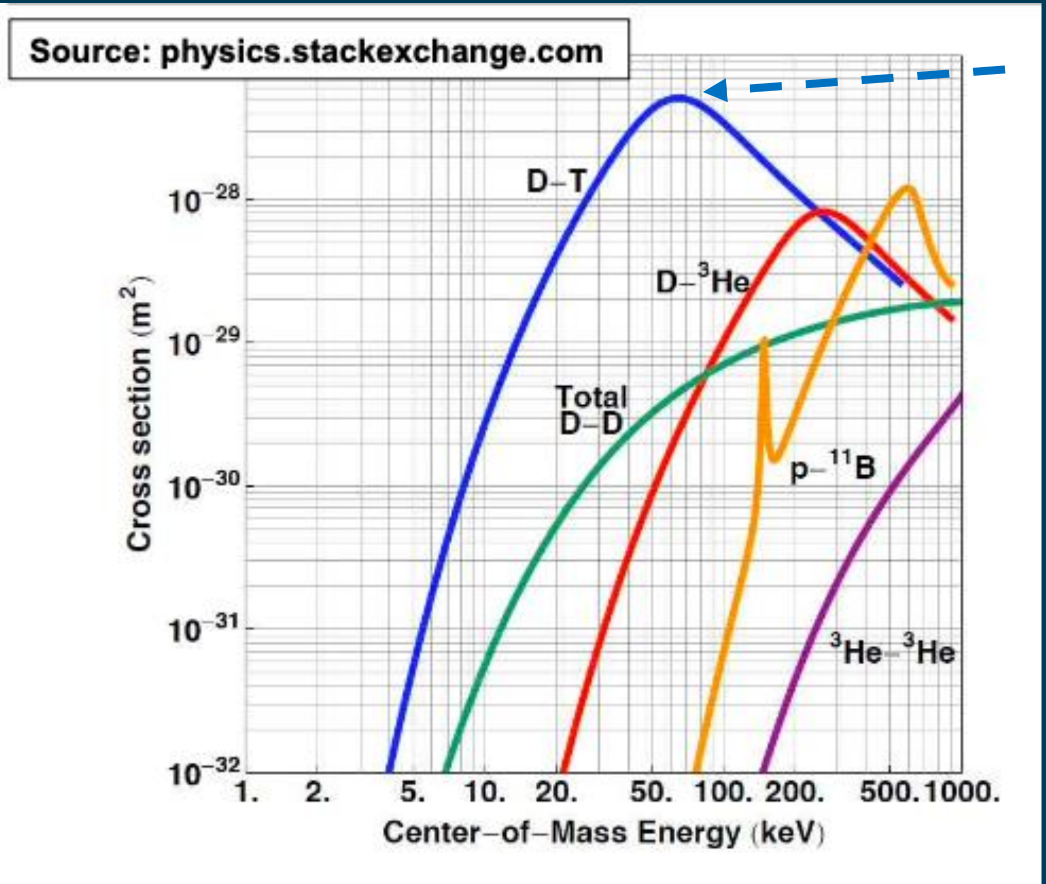
iter

china eu india japan korea russia usa

Outline

- Introduction: what is ITER
- The ITER site today and progress on some key components
- Assembly progress and timeline to First Plasma
- ITER initiatives for the Private Sector and open sourcing
- Concluding remarks

A Fortunate Anomaly: $\sigma_{D-T} \sim 100\sigma_{D-D}$



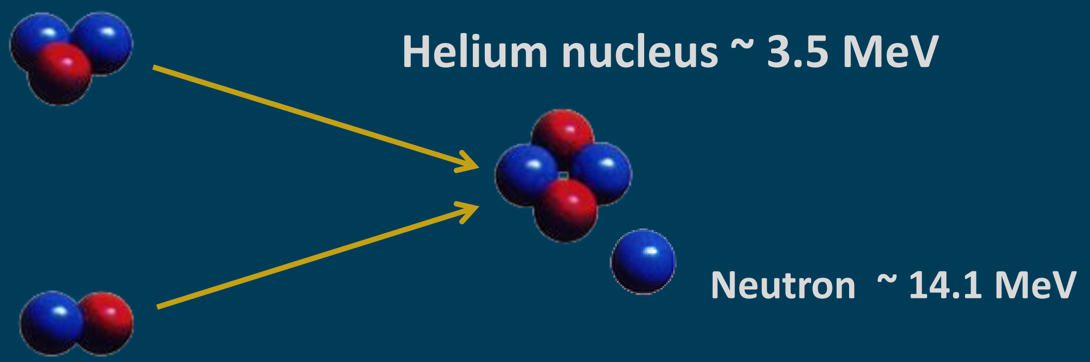
Bretscher Resonance (1945)

$$ {}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{5}_{2}He^{*} \rightarrow {}^{4}_{2}He + {}^{1}_{0}n $$

$$ {}^{1}/_{5} \qquad {}^{4}/_{5} $$

3.5 MeV 14.1 MeV

$$ \Delta mc^2 = 17.6 \text{ MeV} $$



Why ITER?

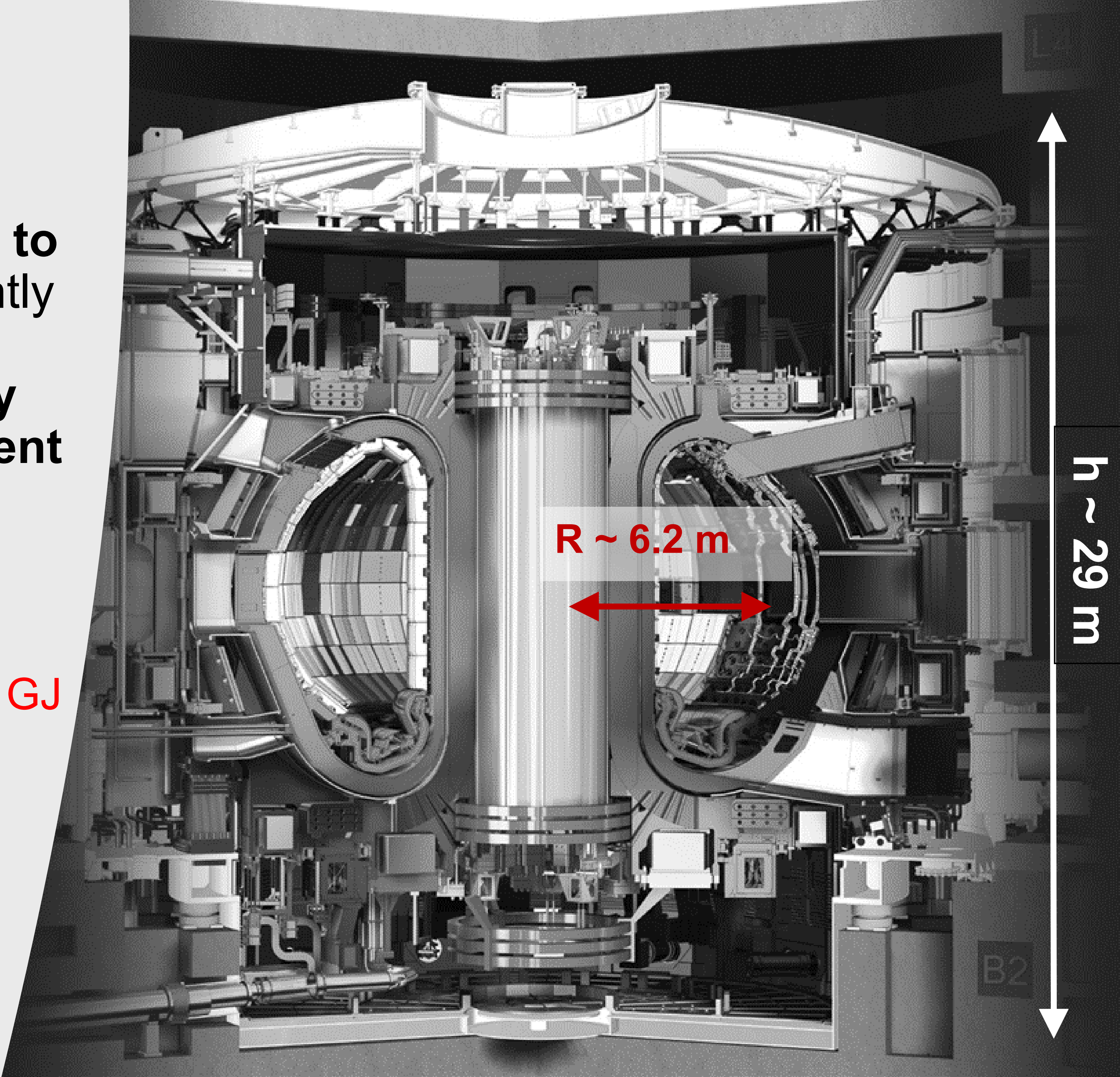
Demonstrate the scientific and technical feasibility of fusion as a source of energy:

- **Q=10** in **D-T** plasmas
- **Stationarity** (400s->3600s)
- **Nuclear**: licensing, maintenance, de-activation, dismantling and waste management.
- Proof(s) of concept of **tritium breeding.**
- **Knowledge management and transfer** to future reactors: codes & standards, etc

The ITER machine

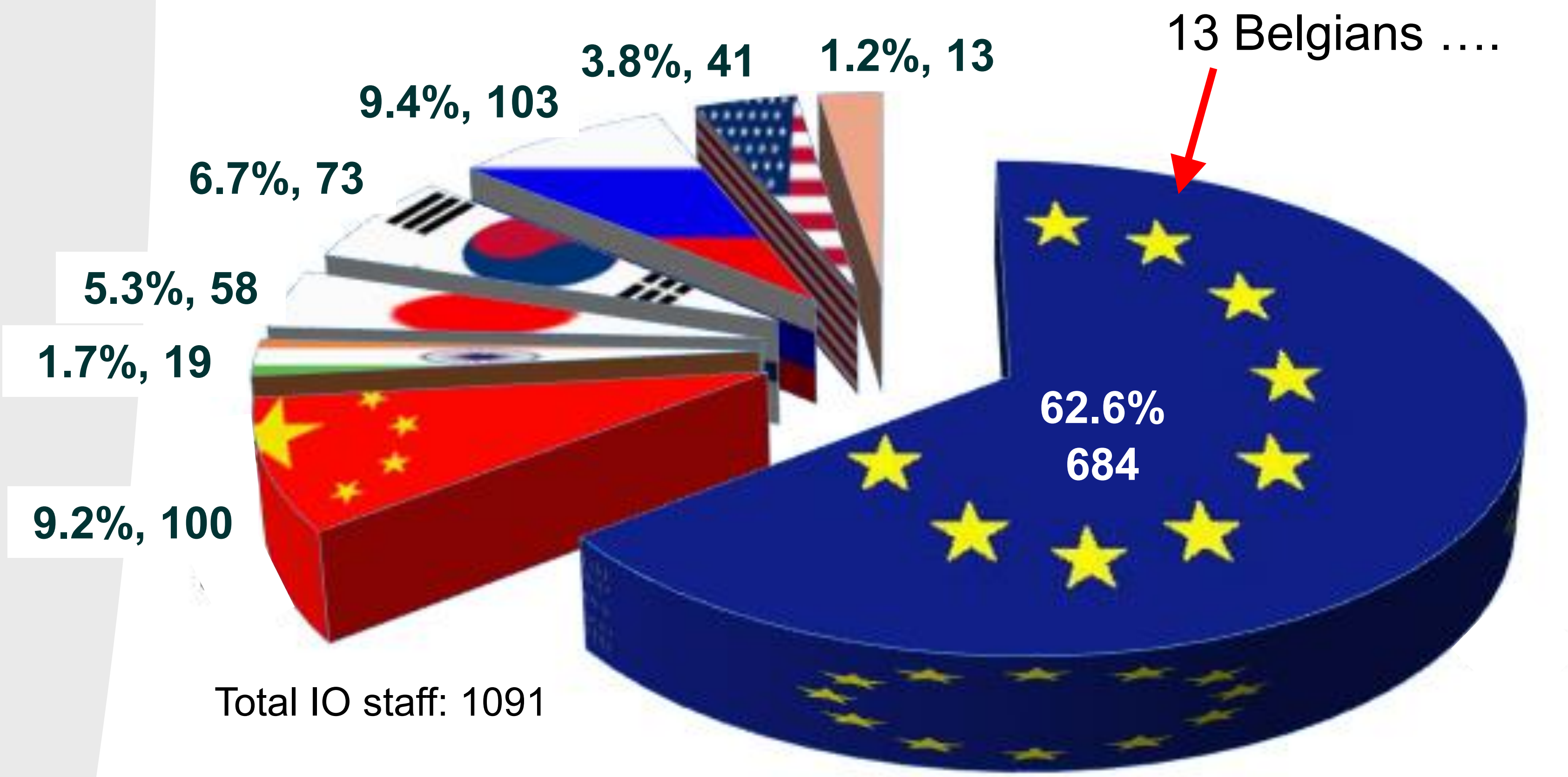
The largest tokamak ever built.
It will produce plasmas that **create more fusion energy than needed to heat them (Q > 1)** and be dominantly heated by the fusion reactions themselves (Q > 5), **with a primary target of Q = 10 at a plasma current of 15 MA** → burning plasmas:

- Major radius: 6.2 m
- B_T = 5.3 T, I_p = 15 MA
- Total stored magnetic energy: ~50 GJ
- Plasma volume: >800 m^3
- Fusion power: 500 MW
- Vacuum vessel volume: 1000 m^3
- Device weight: ~23,000 tonnes
- Cryostat: 29 m wide, 29 m high, volume: 16,000 m^3



ITER construction sharing

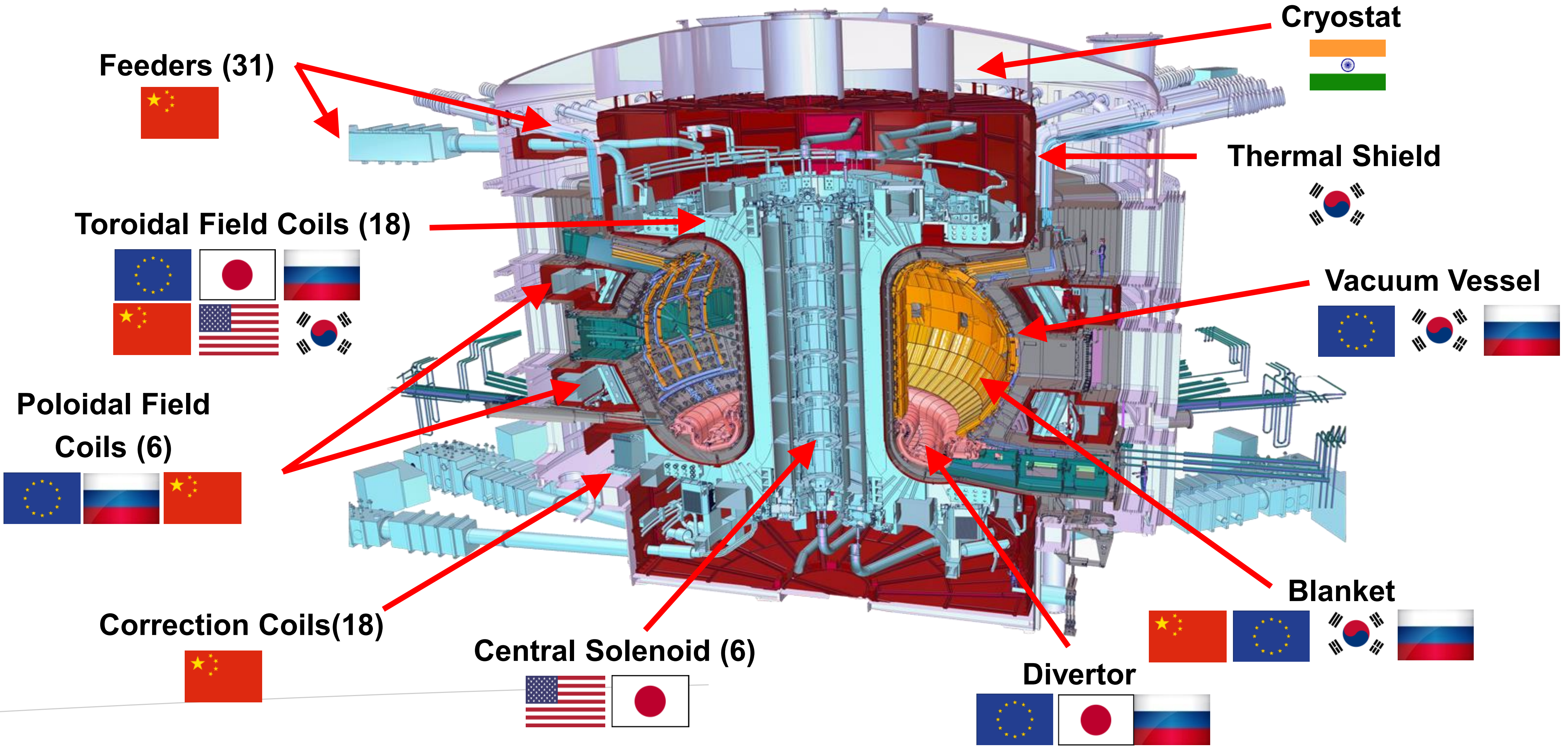
- A unique feature of ITER is that almost all (~90%) of the machine will be constructed through in-kind procurement from the Parties
- Overall sharing:
  - EU: 5/11
  - Other 6 members: 1/11 each



IO Staff distribution by Member (March 2026)

Who manufactures what?

- All intellectual property is shared by the seven members



The ITER site today and progress on some key components

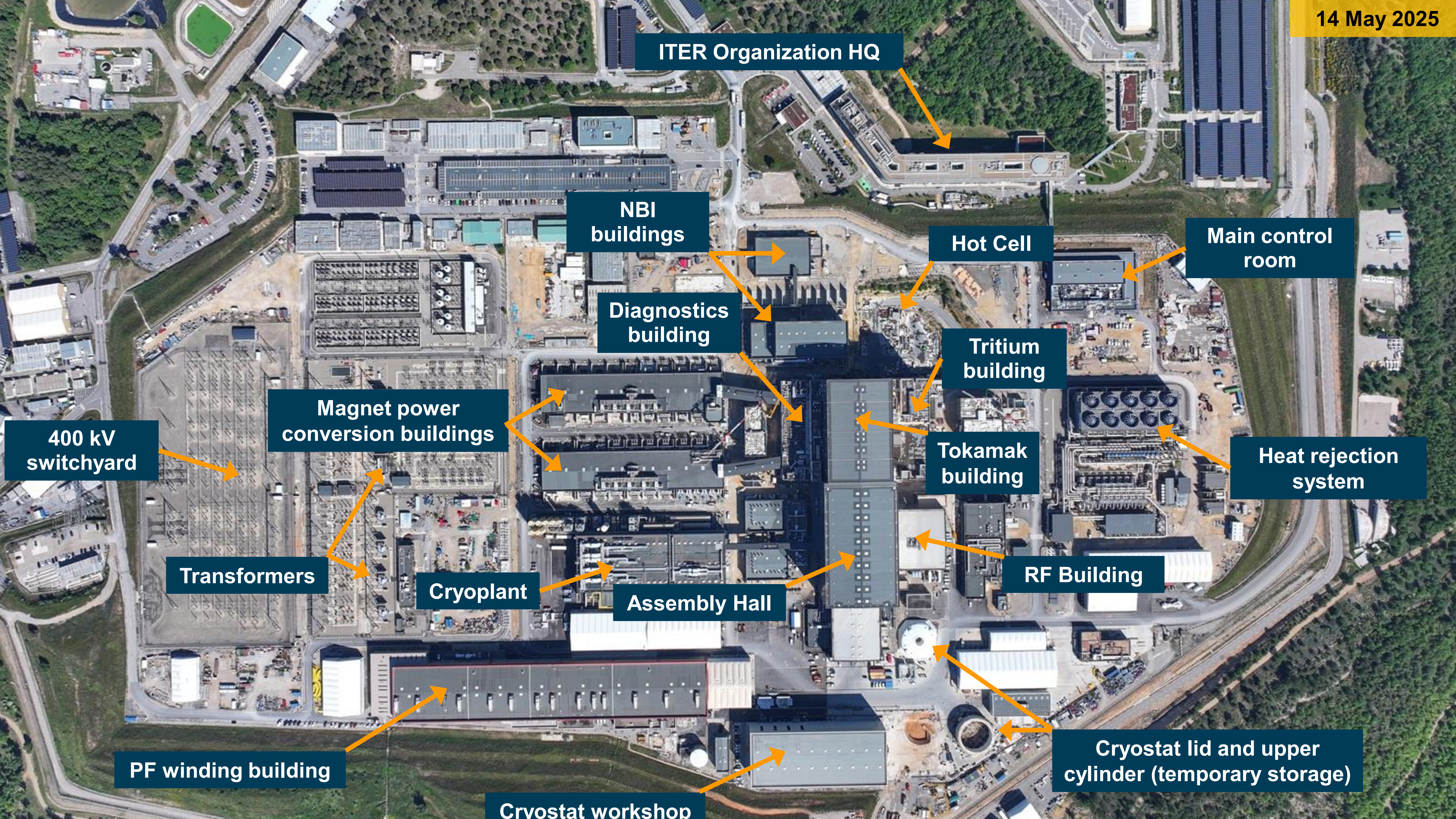
Site construction: before it all started

21 Jan. 2007

French Alternative Energies and Atomic Energy Commission (CEA) acquires ~180 hectares for the ITER Project, near the CEA Cadarache nuclear research centre

1 April 2026

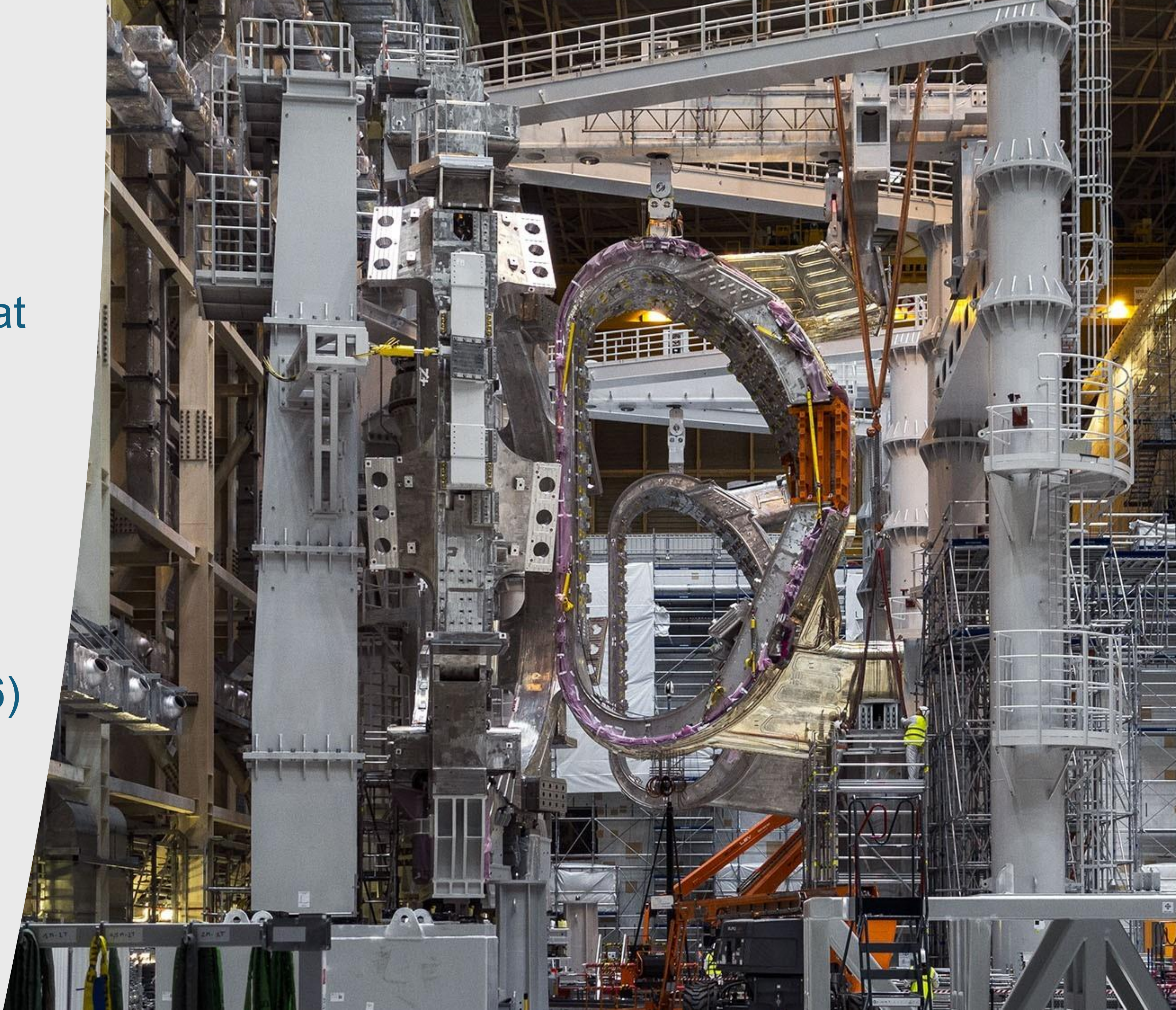
Construction Site in April 2026 (southwest view)


14 May 2025
ITER Organization HQ
NBI buildings
Hot Cell
Main control room
Diagnostics building
Tritium building
Magnet power conversion buildings
400 kV switchyard
Tokamak building
Heat rejection system
RF Building
Transformers
Cryoplant
Assembly Hall
Cryostat lid and upper cylinder (temporary storage)
PF winding building
Cryostat workshop

Vacuum Vessel

- 9 sectors
  (KO: 4, EU: 5) each 440 tonnes
- KO: all 4 sectors (6,7,8,1) at ITER site
- EU: at ITER site:
  Sector 4 (May 2025)
  Sector 5 (Oct. 2024)
  Sector 9 (March 2026)
  Sector 3 (May 2026)
  Sector 2 (target Sept. 2026)

- BUT the VV provided us with a first example of a major assembly issue …



Challenges of FOAK components

- First complete Vacuum Vessel Sector Module (SM) was lifted into the tokamak pit in May 2022 …

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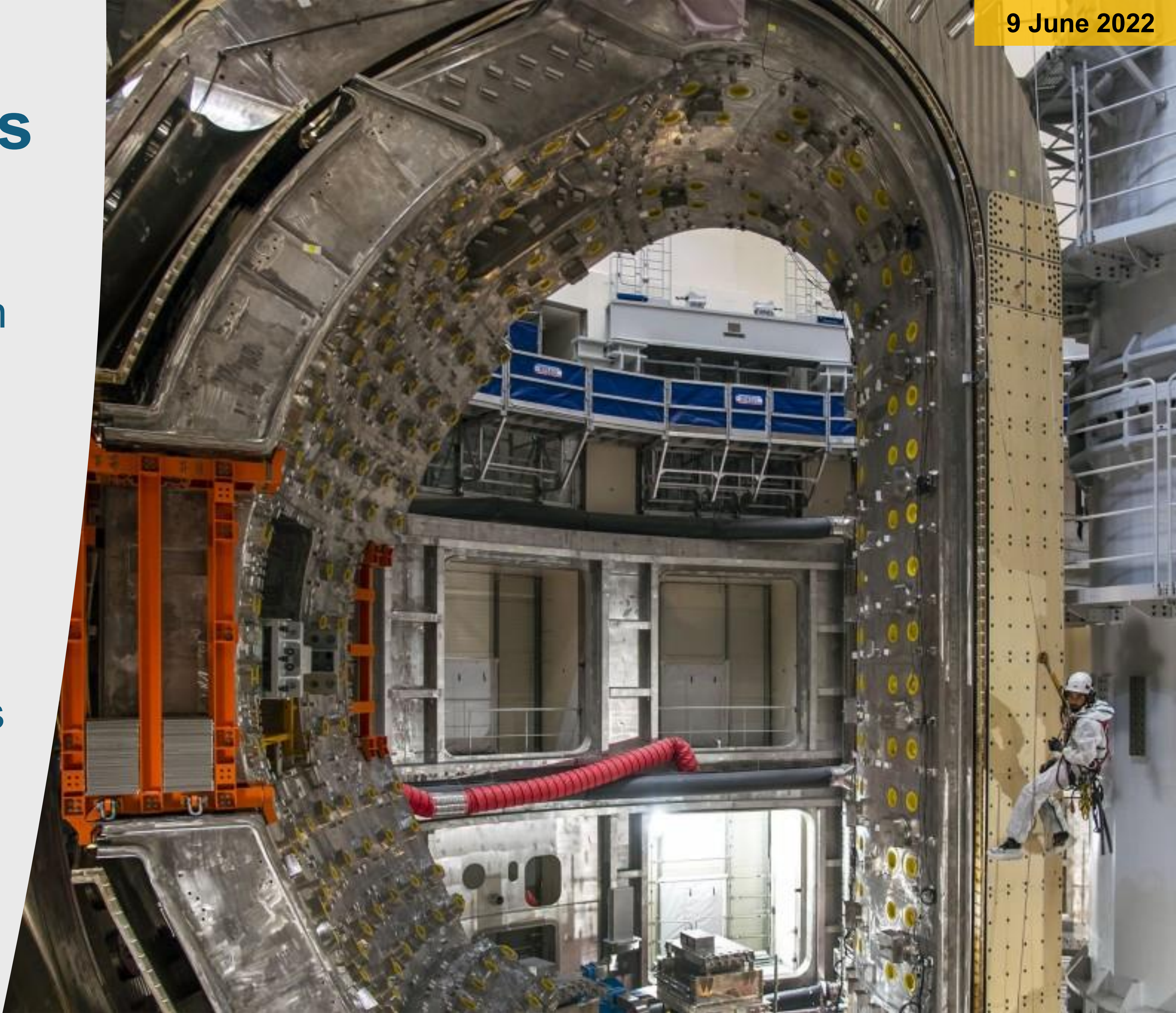
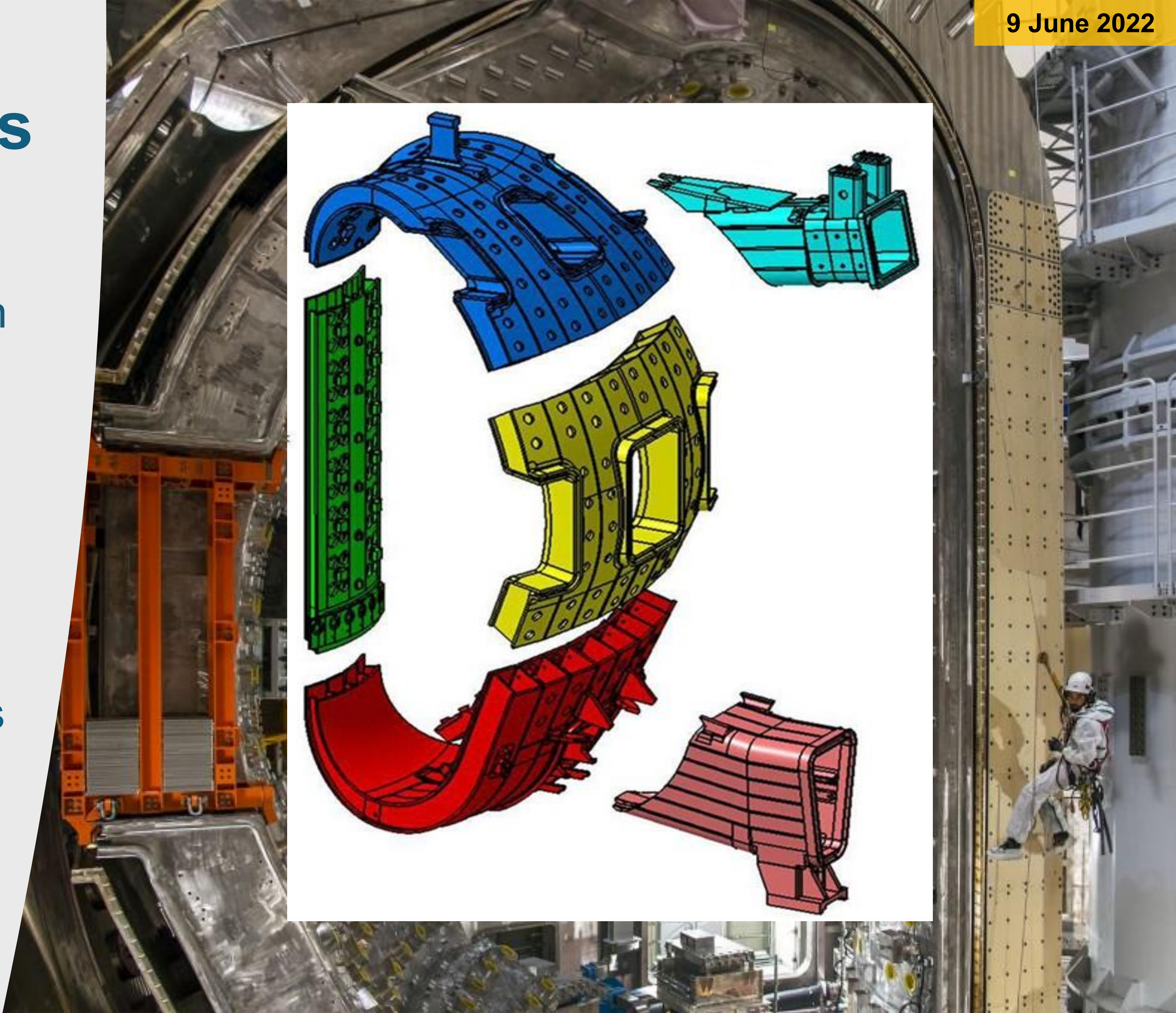
- …. but sector-to-sector welding was reassessed to be too challenging to perform *in-situ*, based on previously identified geometric non-conformities in the field joints

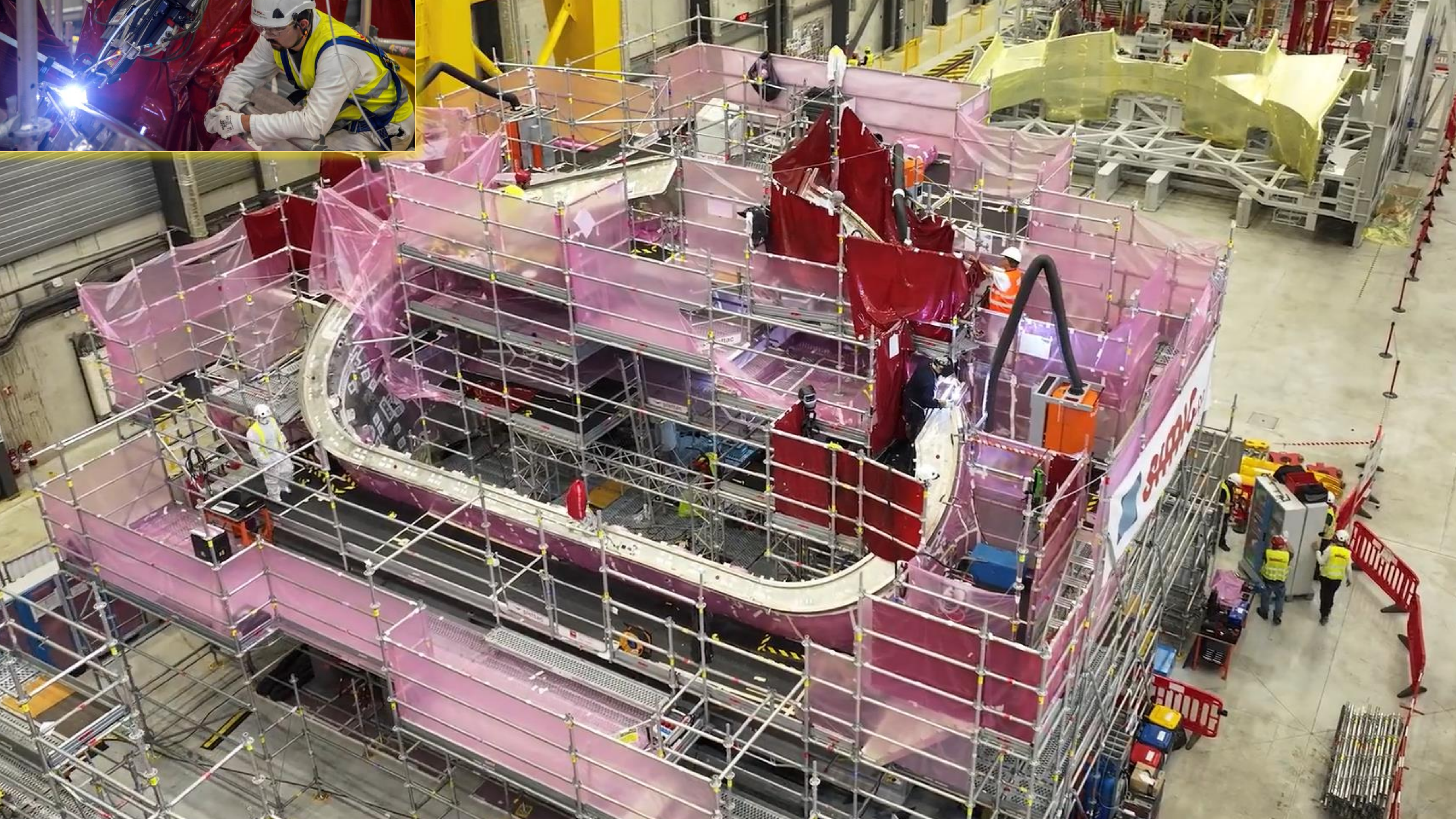


9 June 2022

Challenges of FOAK components

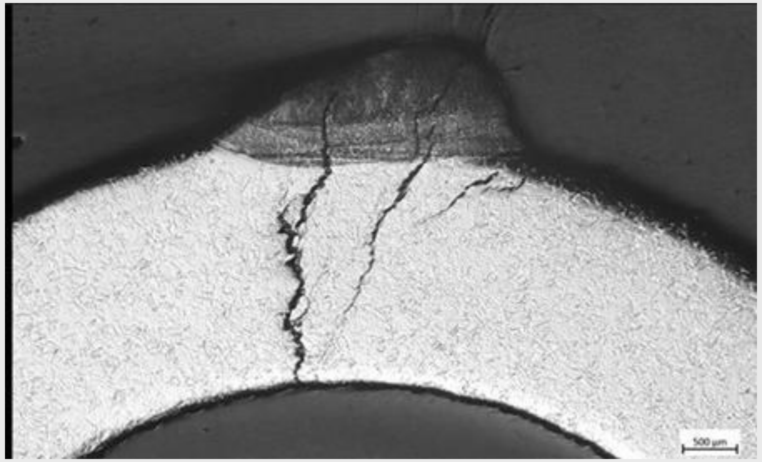
- First complete Vacuum Vessel Sector Module was lifted into the tokamak pit in May 2022 …
- …. but sector-to-sector welding was reassessed to be too challenging to perform *in-situ*, based on previously identified geometric non-conformities in the field joints
- Required complex and time consuming repair process → now complete



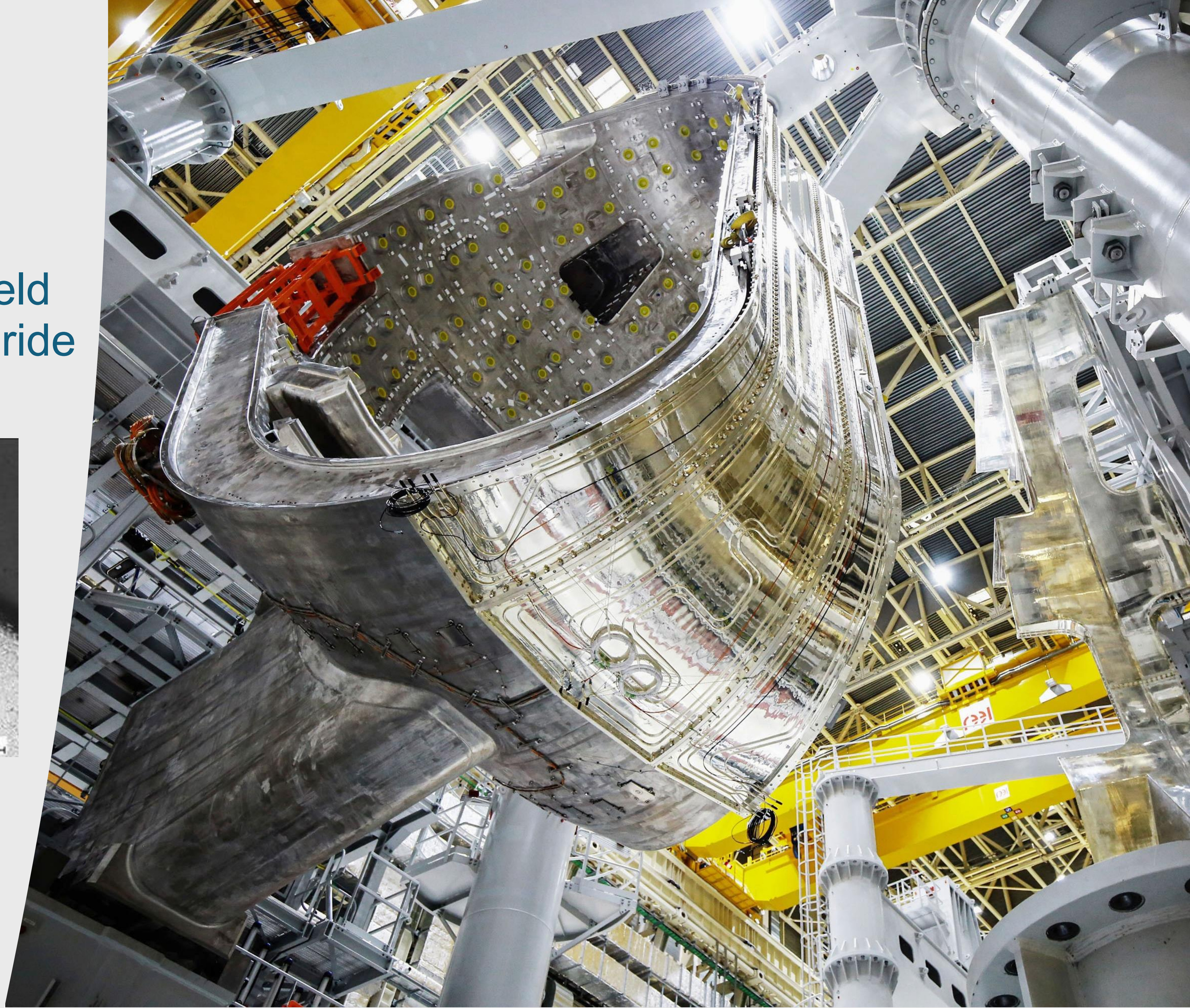


Major issue on tokamak thermal shields

- Leakage identified on shield cooling piping due to chloride stress corrosion.



- Would have rendered the fully assembled tokamak inoperable



Thermal Shield repair

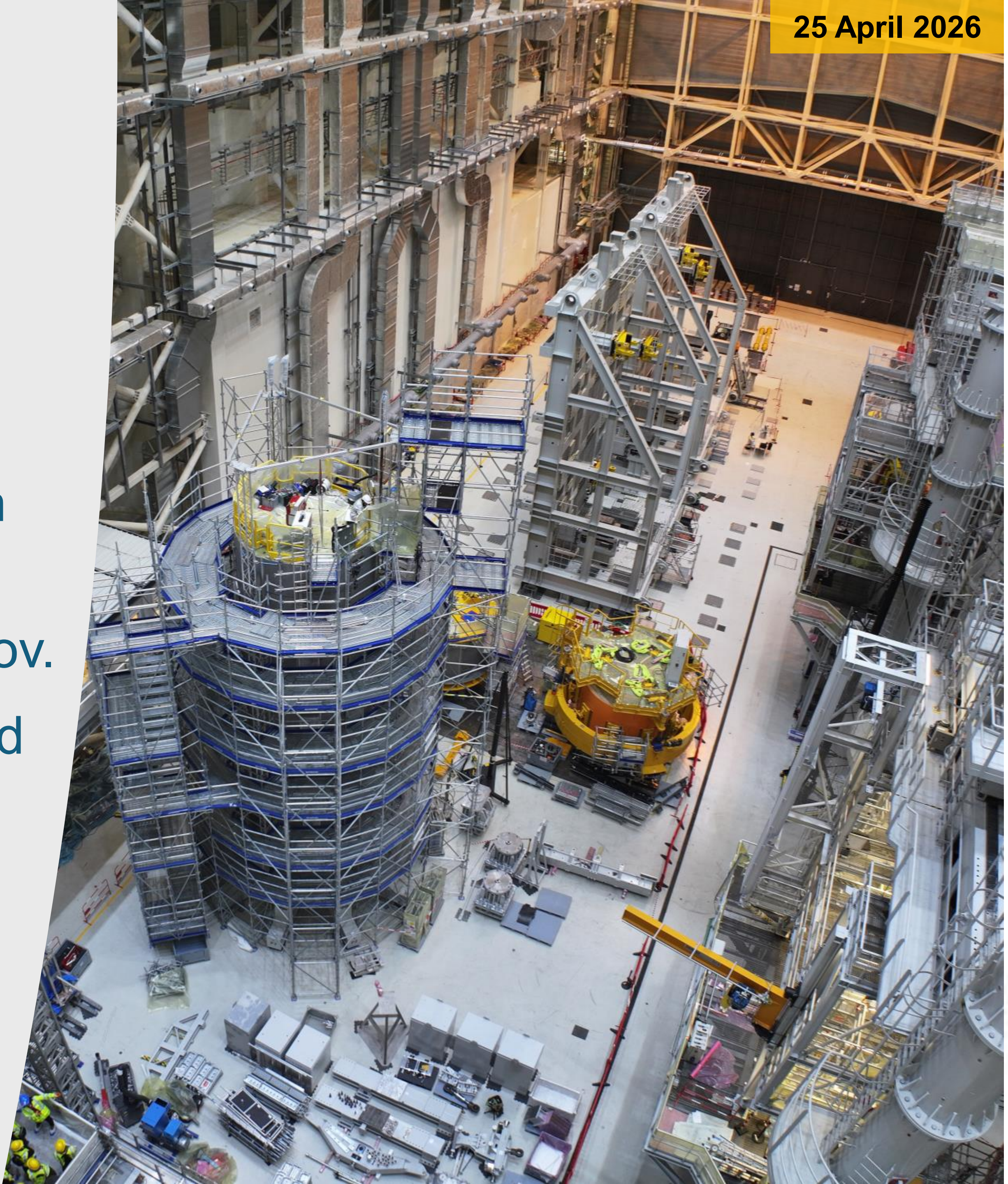
- 2 mm panel machining to eliminate potential corrosion risk
- Replacement of corroded pipes
- Surface polishing (no silver coating) to <0.1 μm roughness → low emissivity at 80 K
- Repairs complete for majority of sectors → well under control

Thermal shield repair

- Same problem with cryostat shields
- Some already captive → old pipes condemned, new ones being added
- Accessible components being repaired/replaced

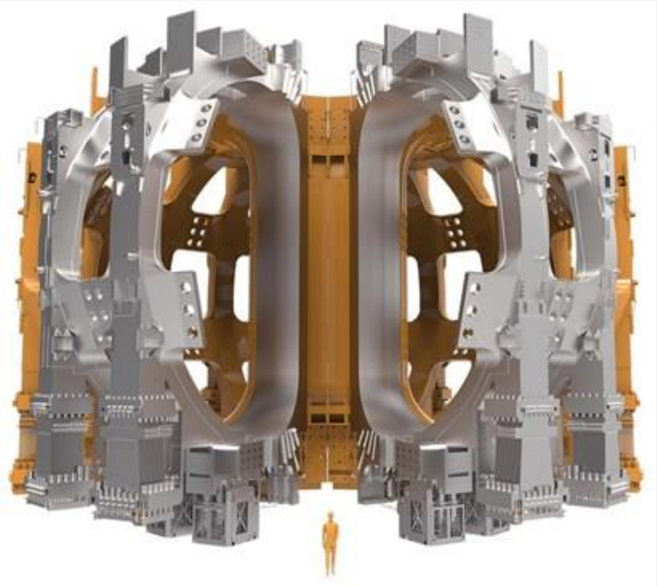
Central Solenoid (CS) assembly

- Nb_3Sn, 13.5 T, 42 kA, 6 modules, ~4 m wide, 18 m tall, 1000 tonnes
- 4th CS module stacked in Jan. 2025
- 5th module stacked 4th Nov.
- 6th module will be stacked later this year
- 7th (spare) delivered
- All other supporting components delivered



Toroidal Field coils

- Nb_3Sn, 11.8 T, 68 kA, 41 GJ, 9 x 17 m, 360 tonnes
- Manufacture complete → all 19 coils on-site by Dec. 2023 (1 spare)
- Supply chain and mass production well established



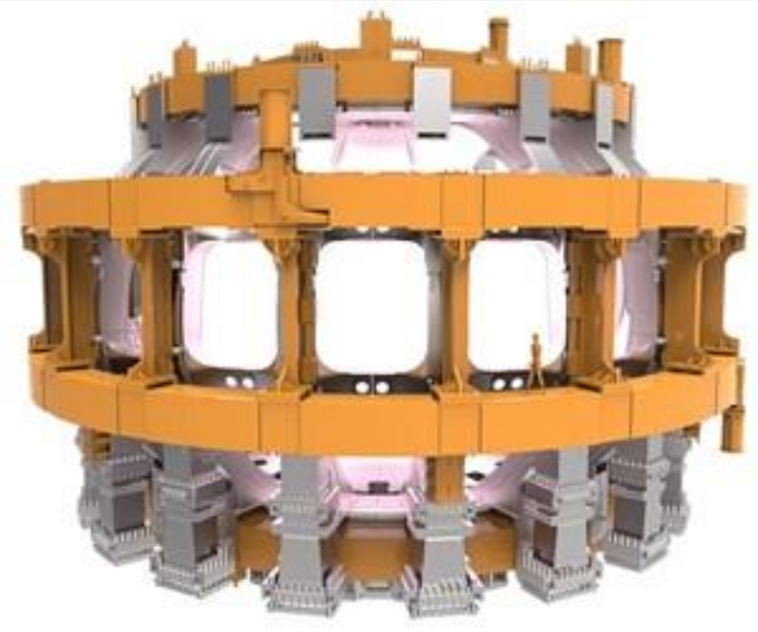
Twin upending tools, each holding a single TF coil prior to docking in SSAT tools

16 July 2025

15 Apr. 2024

Poloidal Field coils

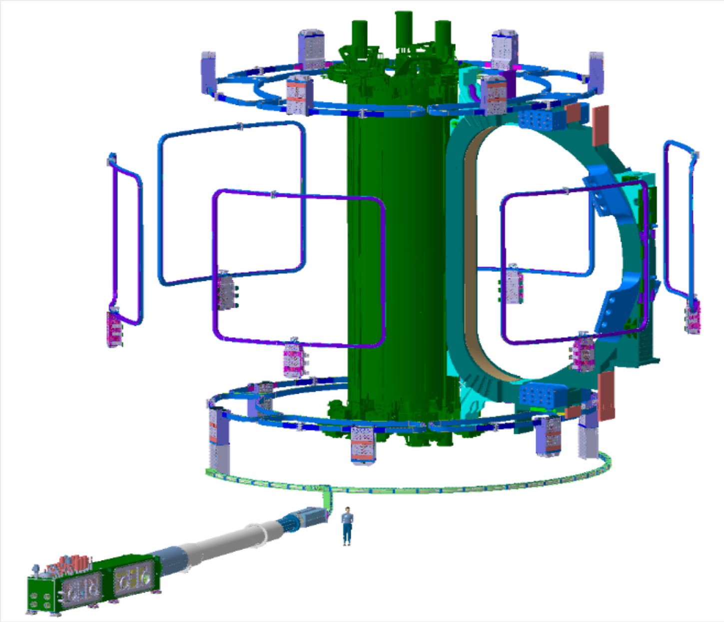
- NbTi, 6 T, 45 kA, 4 GJ
  Largest coils (PF:3,4), 24 m diameter, 400 tonnes
- Manufacture complete and delivered on-site (March 2024)
  PF1 (RF), PF2,3,4 (EU), PF5 (EU) and PF6 (CN) in-pit

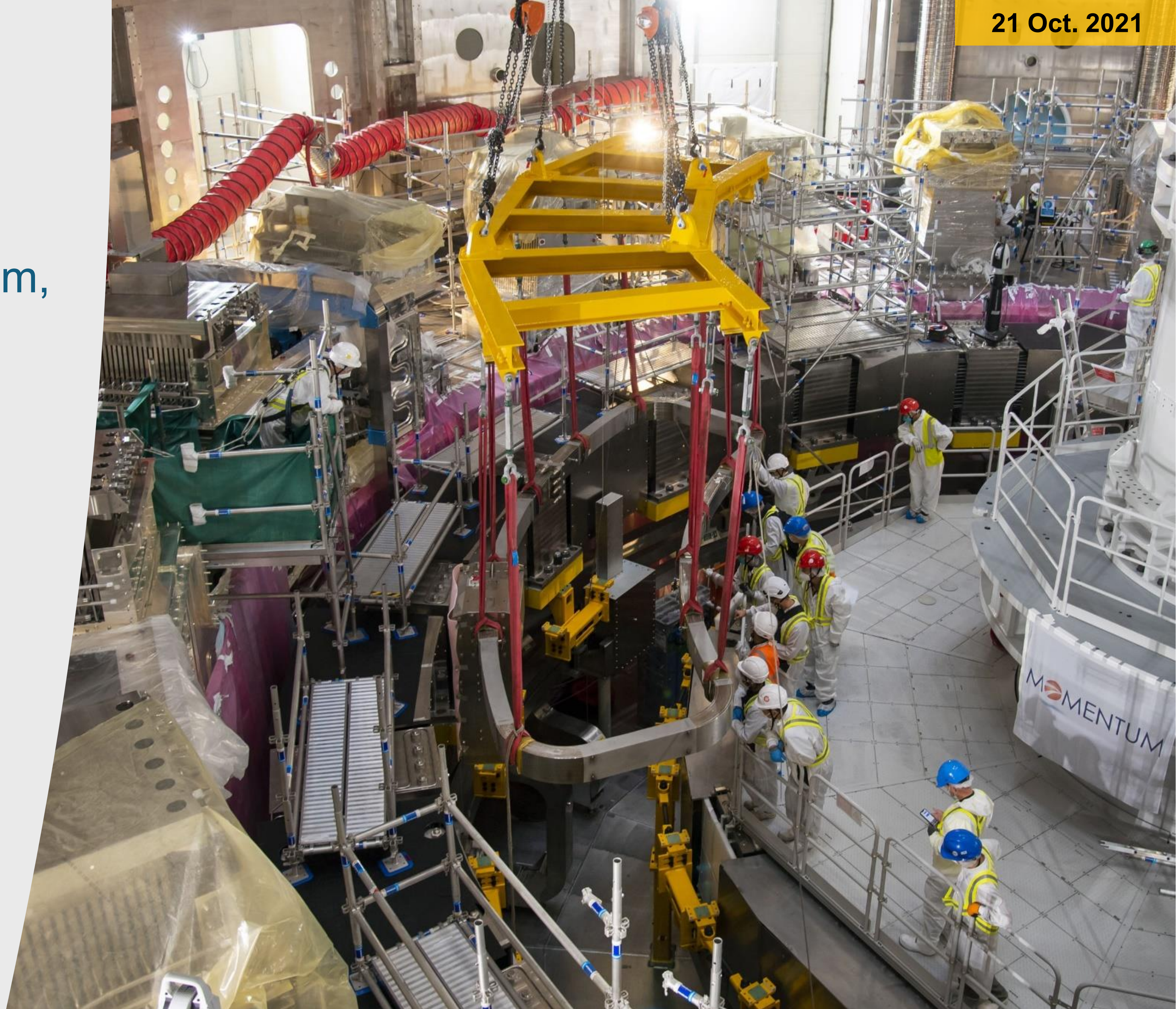


PF3: being moved into storage

Error Field Correction coils

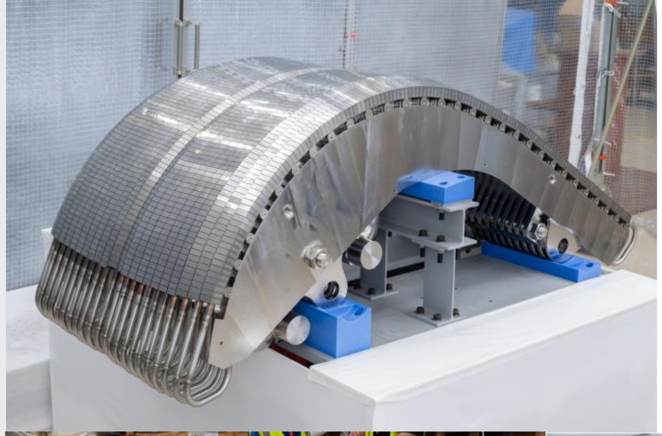
- NbTi, max: ±10 kA, 10 MJ
  6x6 coils, largest 8.4 x 7.2 m,
  total weight 78 tonnes
- All 6 top and bottom coils delivered, production of 6 side coils completed

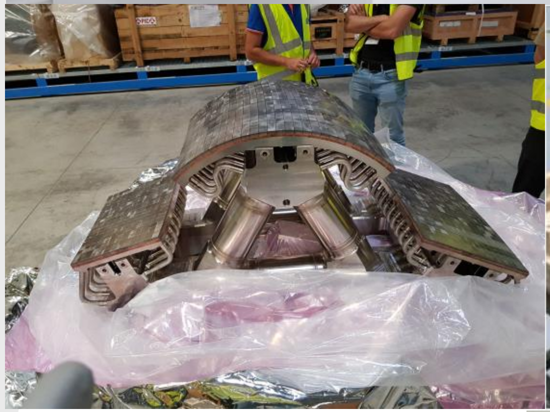


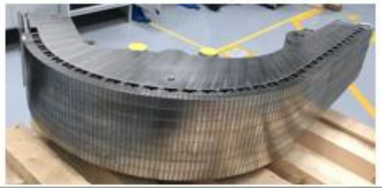


Divertor

- 54 Cassette Assemblies, 8 t each, ~140 m^2 tungsten monoblocks and flat tiles → handles 10-15 MWm^{-2} in steady state
- Full-scale prototypes complete for all major components → supply chains established for manufacture in all concerned DA's → 3 OVT already completed at JA-DA
- Contract for divertor cassette assembly integration awarded to consortium led by SWIP (Chengdu, China)

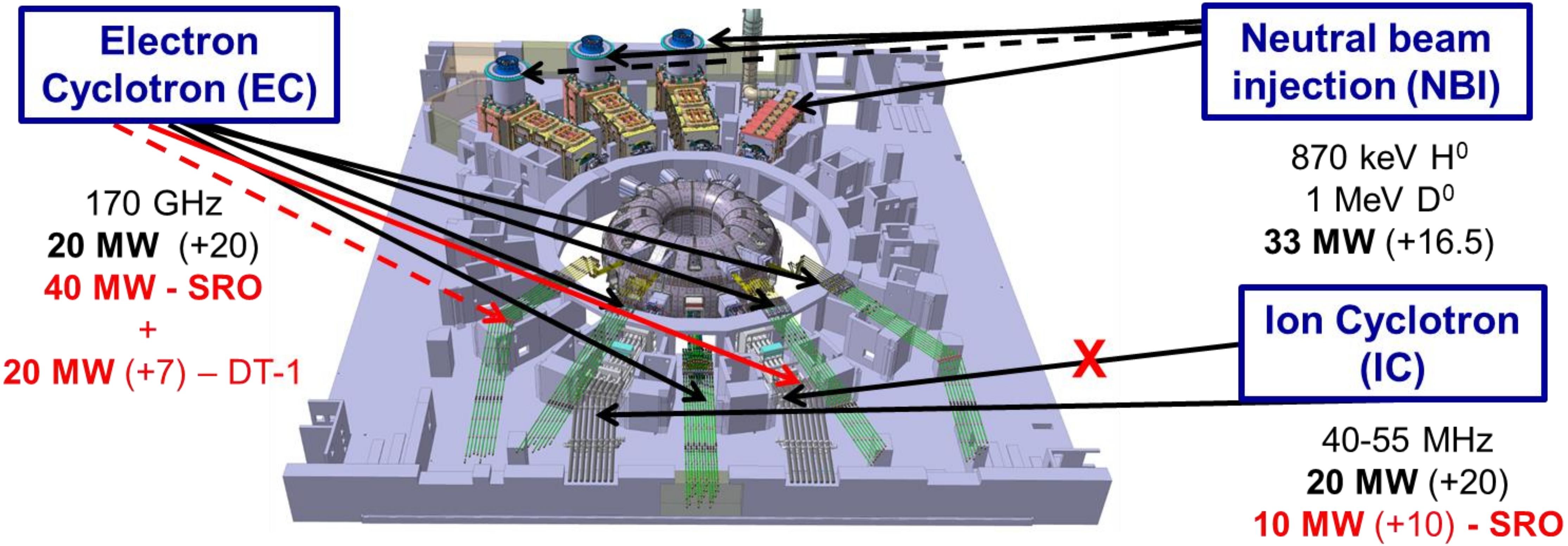


Heating and current drive systems

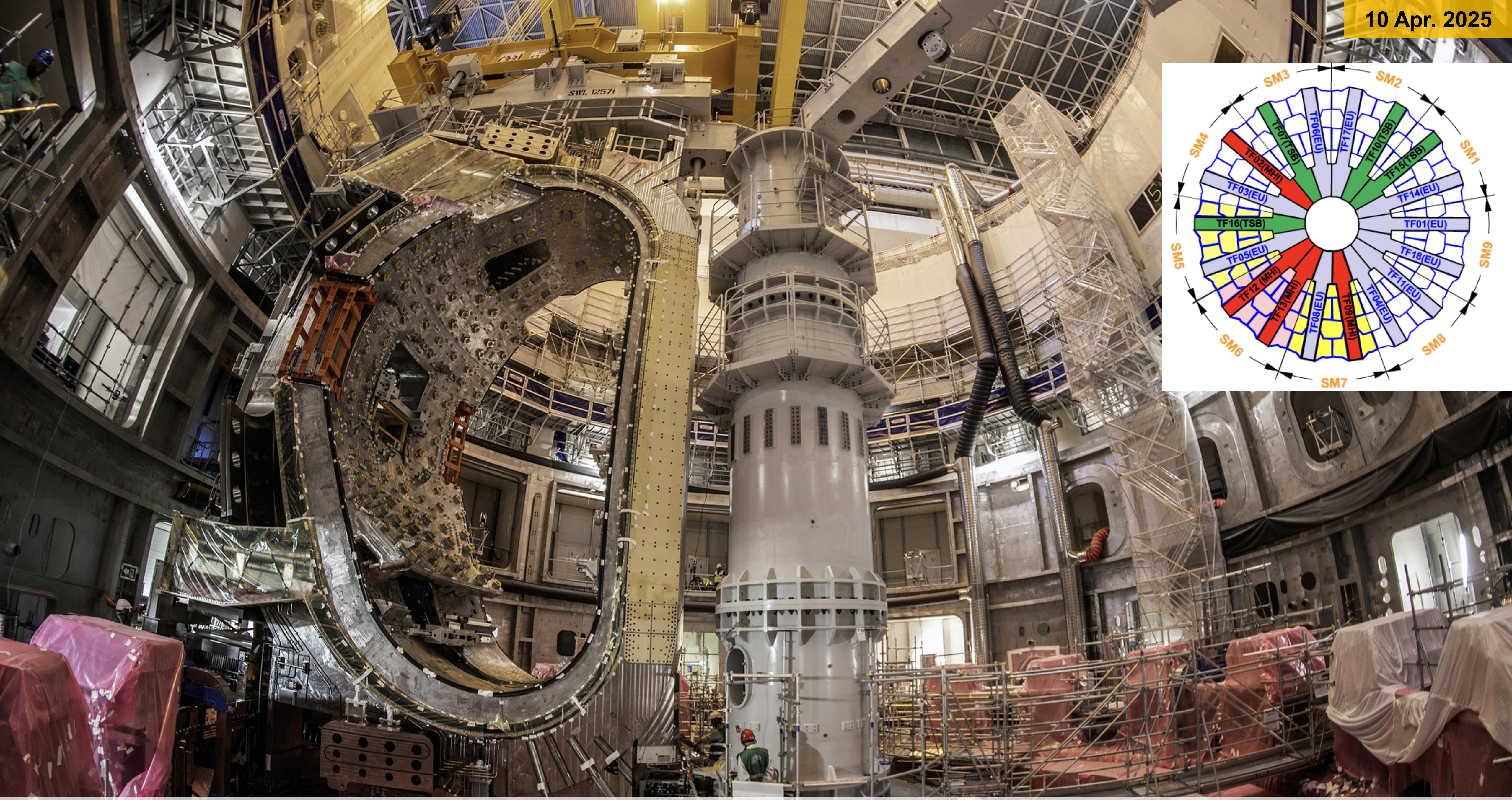
- Up to ~136 MW in the new Baseline
- Increased flexibility for the experimental programme, reduction of risks and achievement of Q = 10 with low neutron fluence



Tokamak assembly and plant

10 April 2025
1st module in place (again)
(youtube.com/@iterorganization)

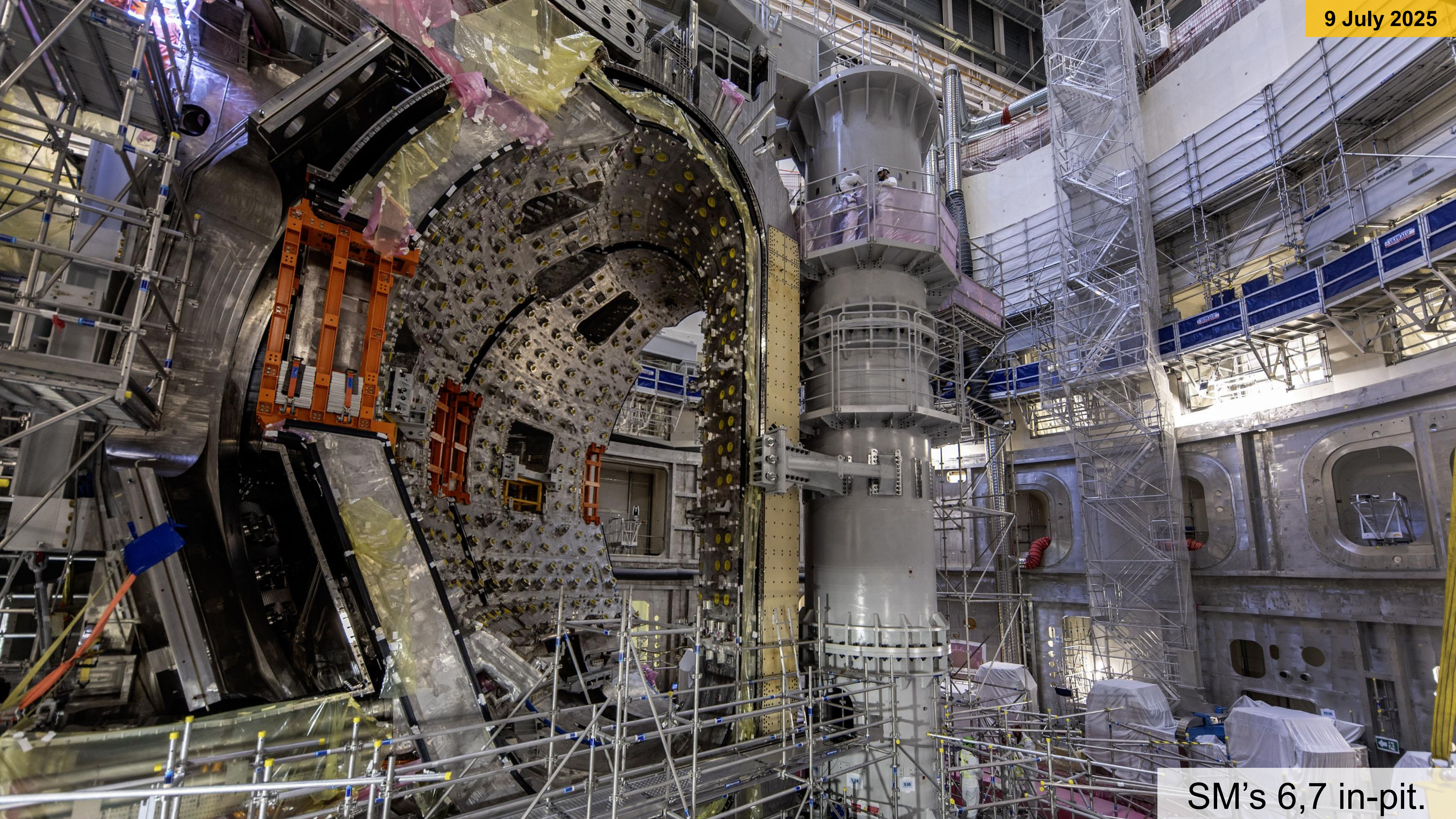
10 Apr. 2025



SM 7 sub-sector assembly completed, March 2025, in-pit installation April 2025

18 June 2025

SM 6 being lowered into the pit



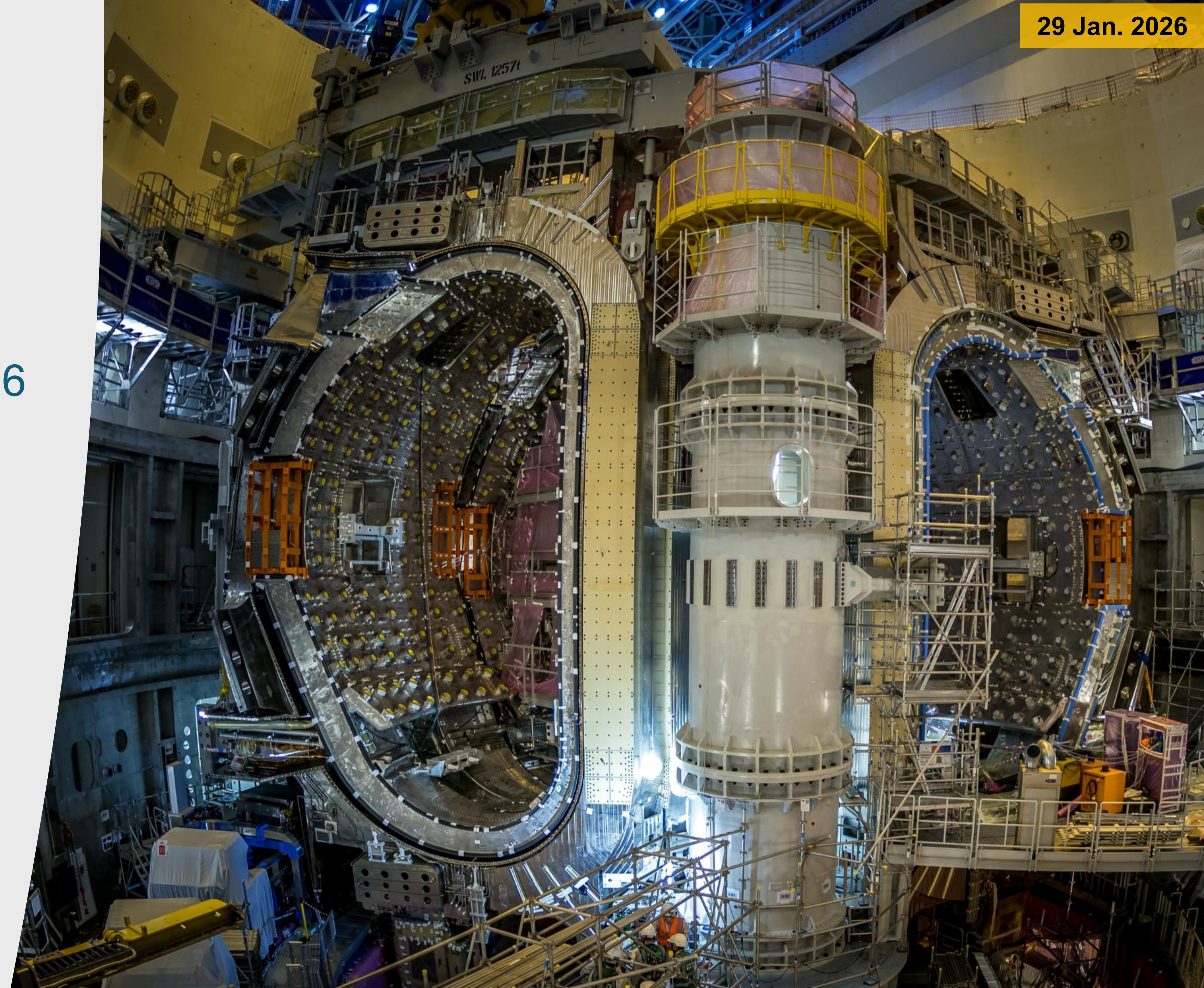
SM's 6,7 in-pit.

24 Nov. 2025

SM 5 on its way

Sector Module production line

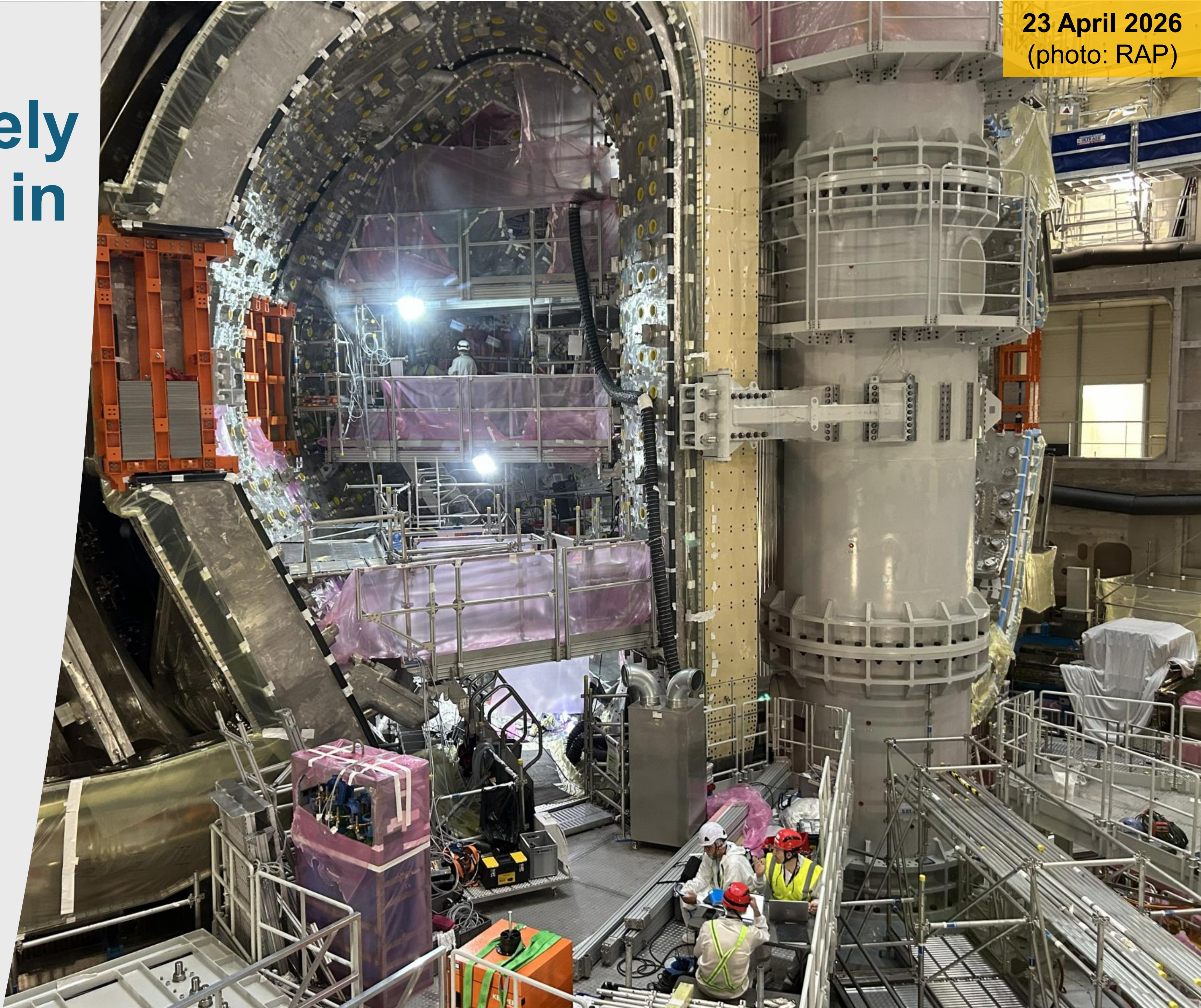
- Sector modules 1 and 4 now on sub-assembly frames
- SM 8, 2nd week Jan 2026
- SM 4 pit transfer in May
- All 9 SM's by mid-2027
- NB: SM assembly duration:
  18 months in 2021
  → 7.5 months (SM 7)
  → 6.5 months (SM 6)



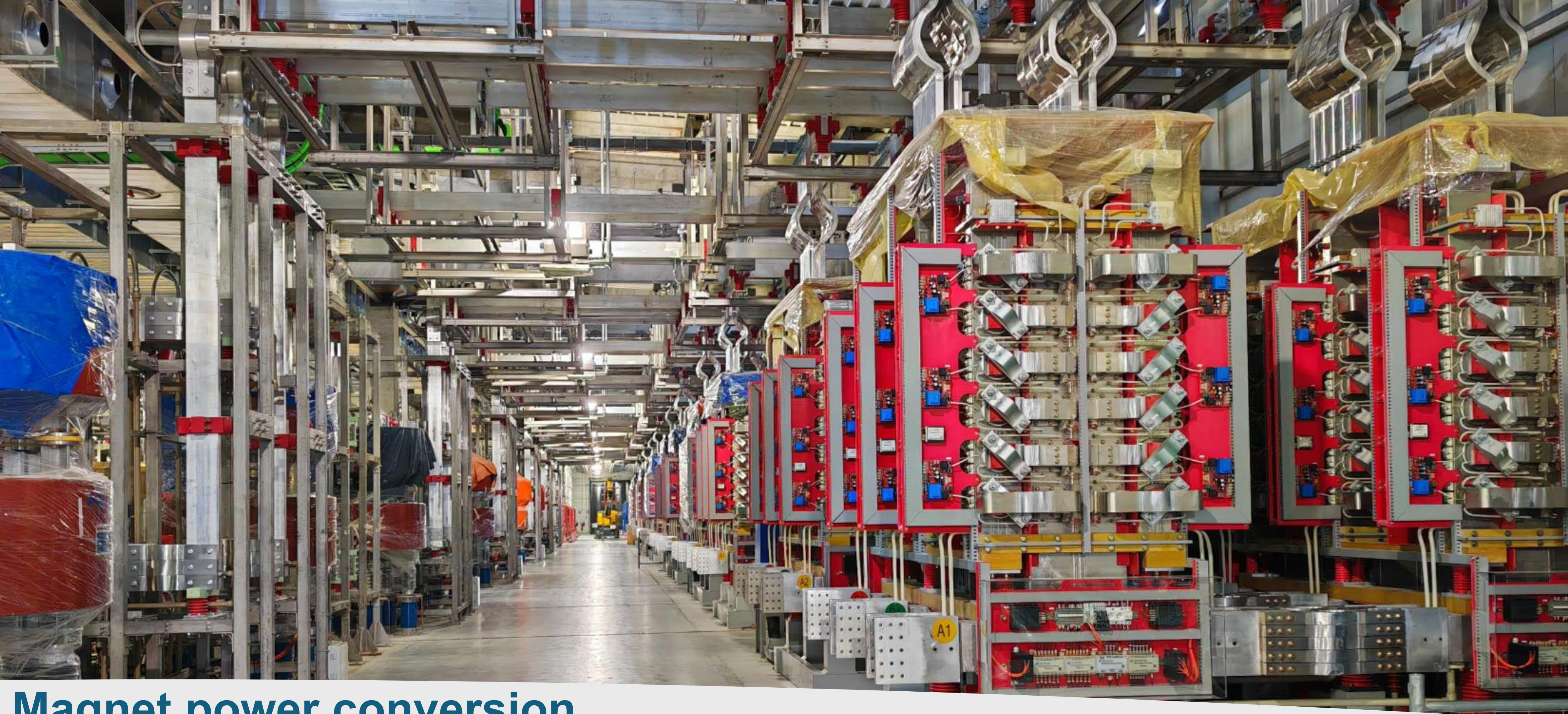
29 Jan. 2026

In-vessel work begins immediately once sectors are in place

- 4-levels of staging installed in each sector following in-pit positioning
- Thousands of “bosses” welded inside each SM for diagnostic sensors and cables
- Sectors will be welded together once all 9 SM’s in place



23 April 2026
(photo: RAP)

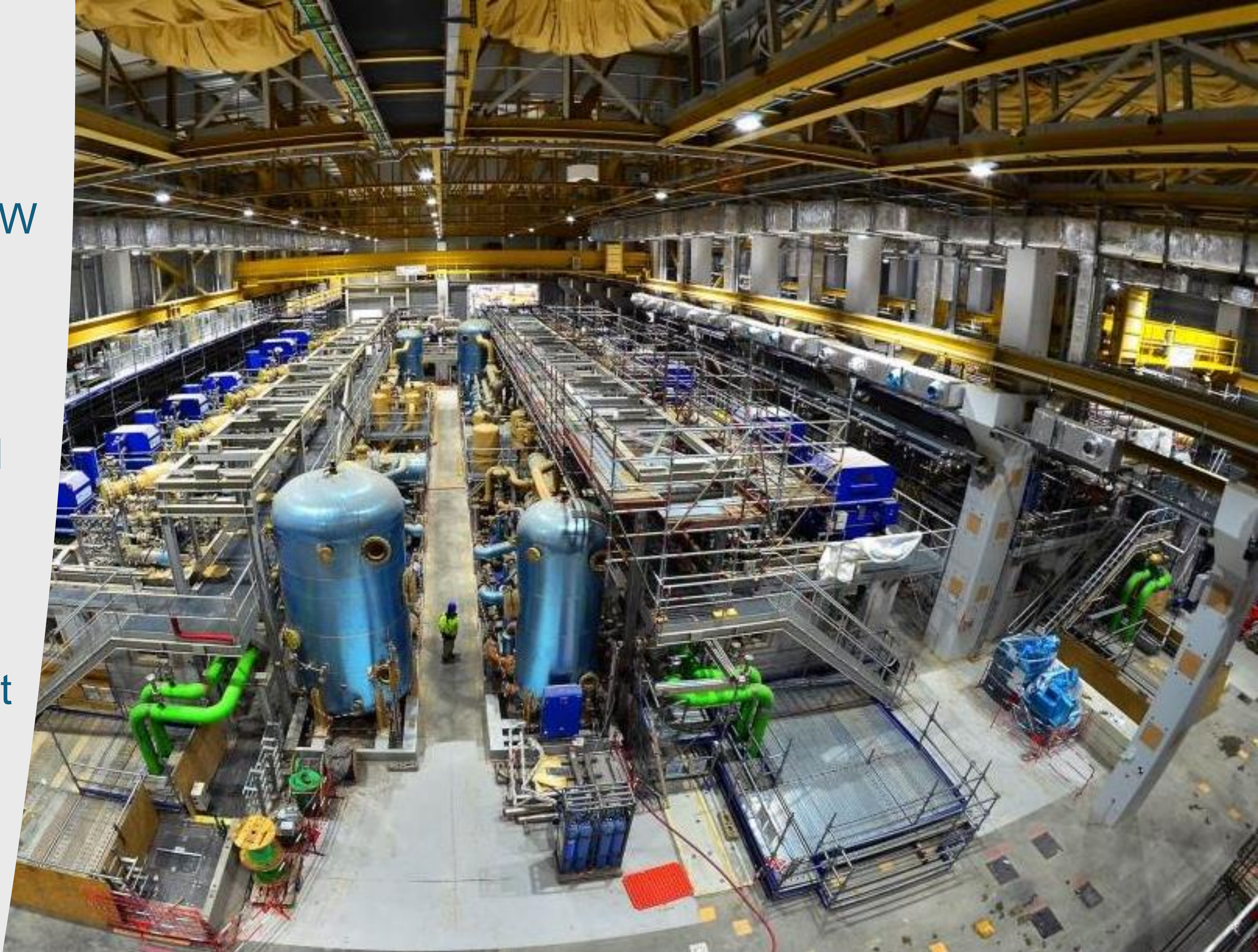


Magnet power conversion

- AC/DC power convertors from China and Korea for PF, TF, CS, CC, VS coils

Cryogenics plant

- Refrigeration: 75 kW @ 4.5 K
- 34 tonnes He inventory
- 40 MW_{elec} installed power
- Commissioning largely completed
- He liquefaction first achieved in Dec. 2024



ITER re-baseline and timeline

2024 ITER re-baseline

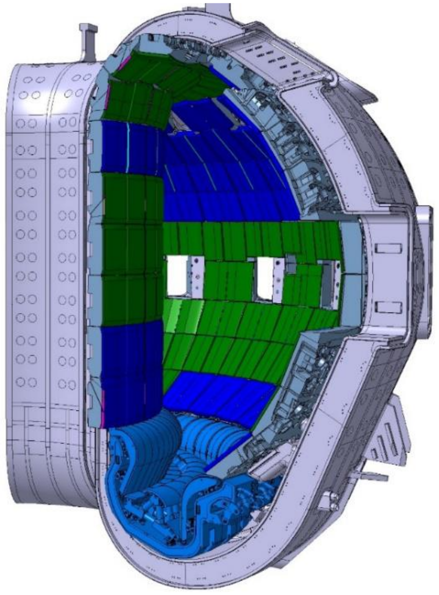
- Target robust achievement of ITER Project goals, in view of past challenges (delays due to the Covid-19 pandemic, technical challenges in completing FOAK components and in nuclear licensing)
- More realistic and reliable assembly – commissioning – operation
- Achievement of earliest start of the ITER Nuclear Phase (DD operation) and minimization of technical risks → a new 1st phase **"Start of Research Operation" (SRO)**
- Stepwise safety demonstration → **2 new DT phases (DT-1,2)**

- Key elements of the new baseline driven by physics/operations:
  - First Wall: beryllium (Be) → tungsten (W), start with inertially cooled W wall
  - Optimized additional heating mix → ease path to Q = 10 with added W

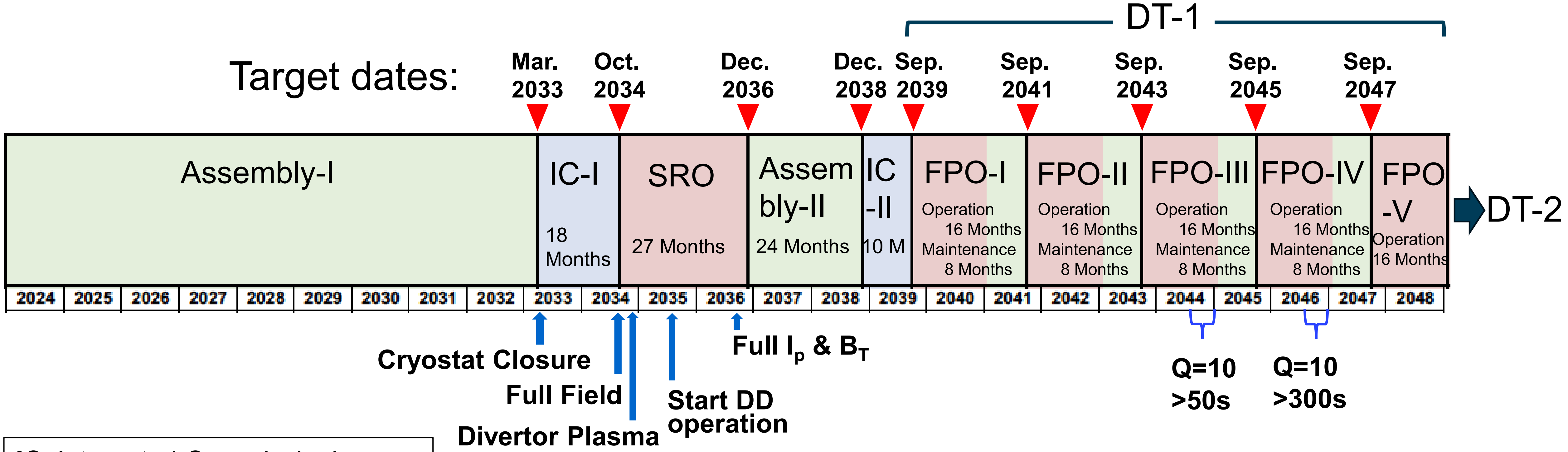
R. A. Pitts et al., NME **42** (2025) 101854

Why change to a tungsten First Wall?

- Fusion reactor relevant
- Physics basis for tokamak operation with W walls is much stronger than it was at start of ITER construction
- Several issues with Be as PFC:
  - Erosion lifetime
  - Tritium retention
  - Low melting point
- Major benefit in assembly complexity and avoid costly later wall changeout



Overall Project Schedule for new Baseline



IC: Integrated Commissioning
SRO: Start of Research Operation
FPO: Fusion Power Operation

- Main target dates:
  - Cryostat closure: 2033, Start of DD H-mode operation: 2035
  - Full plasma current and toroidal field operation: 2036
  - Start of DT operation: 2039, Q ≥ 10: 2044
- Nov. 2024: ITER Council 35 endorsed the overall approach proposed for the 2024 Baseline

Stepwise Safety Demonstration

- ITER is a very large step from present day magnetic confinement devices
- Complexity, large uncertainties and very ambitious project goals make a safety demonstration in “one go” very challenging

Phase 1: DT-1

- A first phase of safety demonstration of ITER operation
- Focused on the achievement of specific project goals (Q = 10, 300-500 s)
- Limited neutron fluence (1% of present “end-of-life” Project Specification) **→ ~3 x 10^{25} neutrons**

Phase 2: DT-2

- Second phase of safety demonstration with knowledge acquired during DT-1
- Attain lifetime neutron fluence **→ 3 x 10^{27} neutrons**

Initiatives for Private Sector and Open-sourcing

Near-term return on the ITER investment

- Rapid learning platform for fusion workforce
  - Unique opportunity to learn realities of complex assembly
  - ITER is a common resource for the world fusion community
- De facto global supply chain for fusion
- Private sector engagement:
  - Access to ITER documents, software, scientific committees, exchange of visits etc.

28 April 2025

ITER and Private Fusion Sector

- Two open doors events for private fusion collaborators in 2024, 2025
  - 350 participants in April 2025
  - Start-ups, industrial suppliers, researchers, advocates, investors, ITER and DA reps.
  - Third event happening now!
- Opening the International Tokamak Engineering Physics Activity (ITPEA) and ITER Integrated Modelling Suite (IMAS) to the private sector (see here)

Delegates at the 2nd ITER Private Sector Fusion workshop

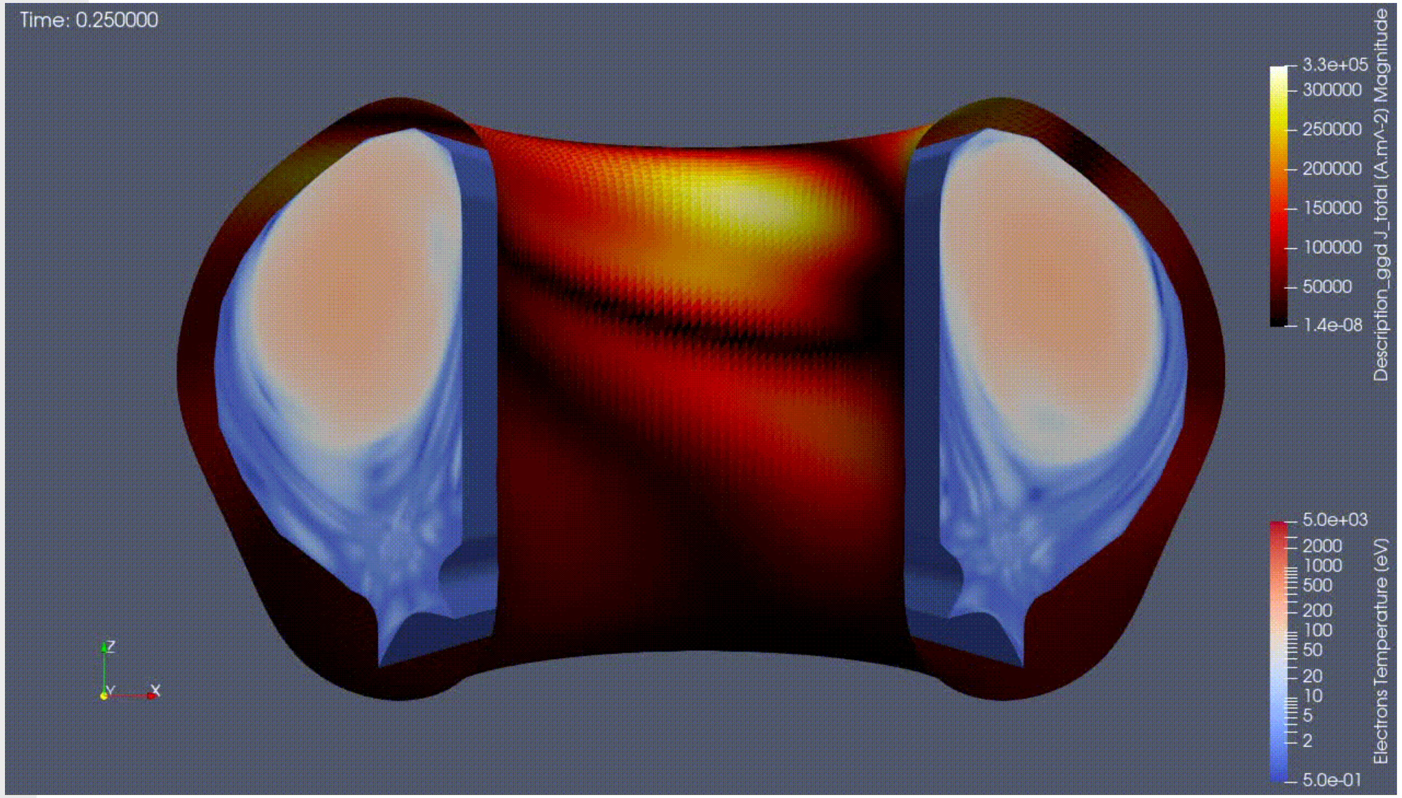
Concluding remarks

- ITER turned a corner in 2023 and performed at a record rate of execution in 2024-25.
- Major restructuring
- Recovery of trust with the French Nuclear Regulator
- Repair of components and restructuring of assembly contracts
- Development of a new Baseline with many improvements and new concepts

Reserve

ITER open sourcing

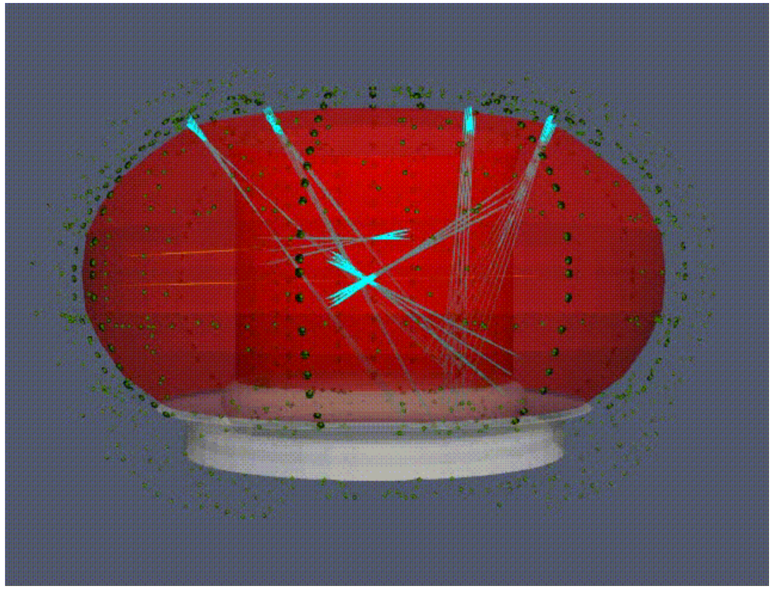
- IMAS provides standard models/apps to support integrated modelling and data analysis of fusion plasmas
  - IMAS built around a standard way of describing fusion data allowing creation software that can be applied to all devices
  - Important for validation and training future ITER users
- IMAS data dictionary, access, visualization tools and physics models <u>released as open source</u> in Dec. 2025
  - See https://github.com/iterorganization



Vertical Displacement Event inducing currents in vacuum vessel

IMAS-Paraview

Diagnostic views



Completely revised ITER Research Plan (IRP) an integral part of new Technical Baseline

- Robust plan, developed with strong involvement of ITER Members' communities, to achievement of Project's goals including risk minimization/retirement and facilitating licensing
- Compensates some of overall Project delay by more rapid progression to 15MA and Q = 10

R. A. Pitts et al. Nucl. Mater. Energy **42** (2025) 101854
A. Loarte et al. Plasma Phys. Control. Fus. **67** (2025) 065023