Progress of ITER, and some perspectives on fusion

Pietro Barabaschi, Director-General

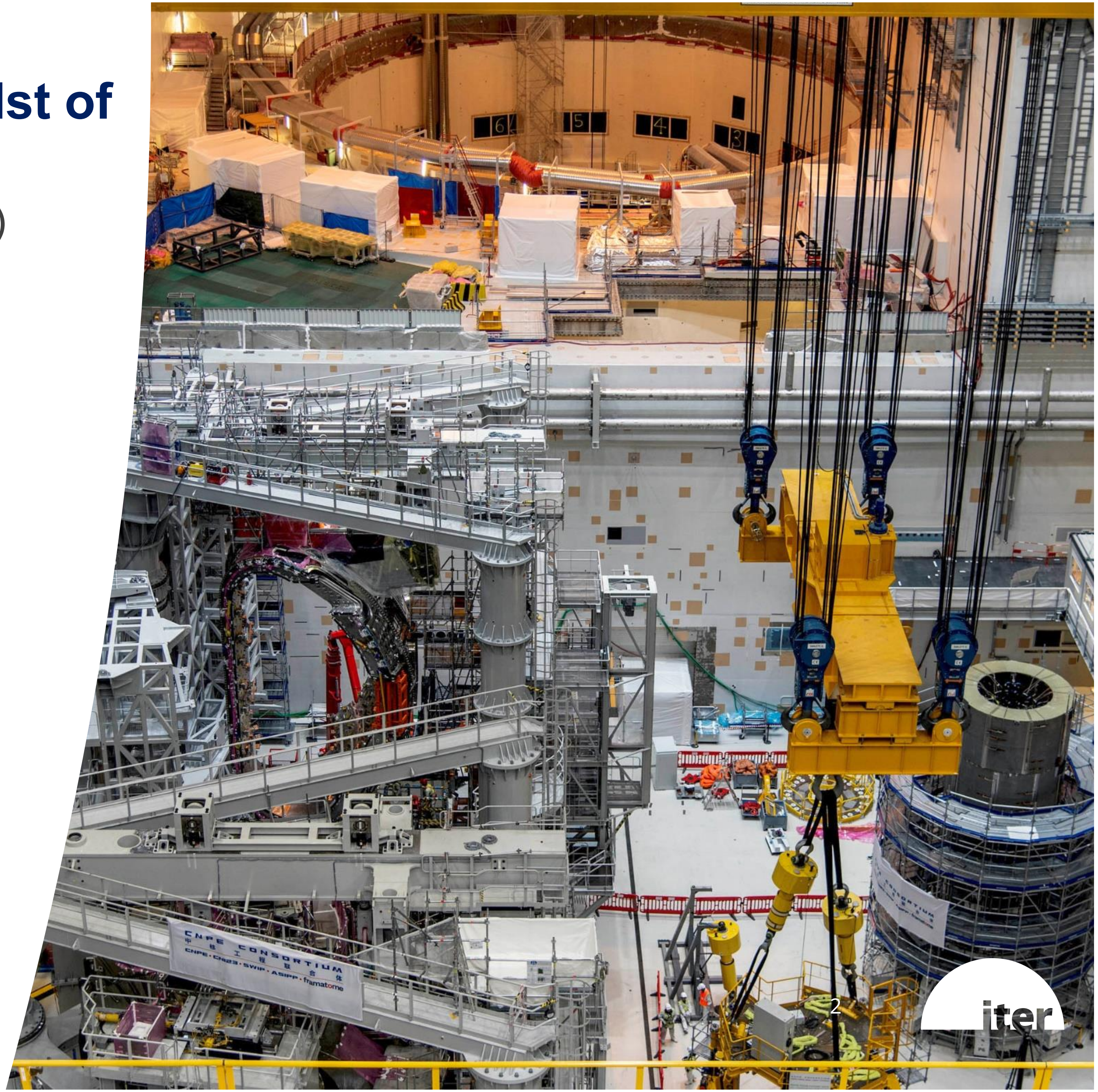
IAEA Fusion Energy Conference, Chengdu, 14 October 2025

iter

china eu india japan korea russia usa

At the last FEC… we were in the midst of

- Setting up the repair of Vacuum Vessel (VV) bevels and VV Thermal Shield (TS) cooling pipes
- Resolving issues of trust with regulator
- Dealing with historically inadequate project execution performance
  - Fixing assembly contracts
  - Reorganising
  - Restaffing
- Dealing with the development of a new Baseline



CHALLENGES OF FIRST-
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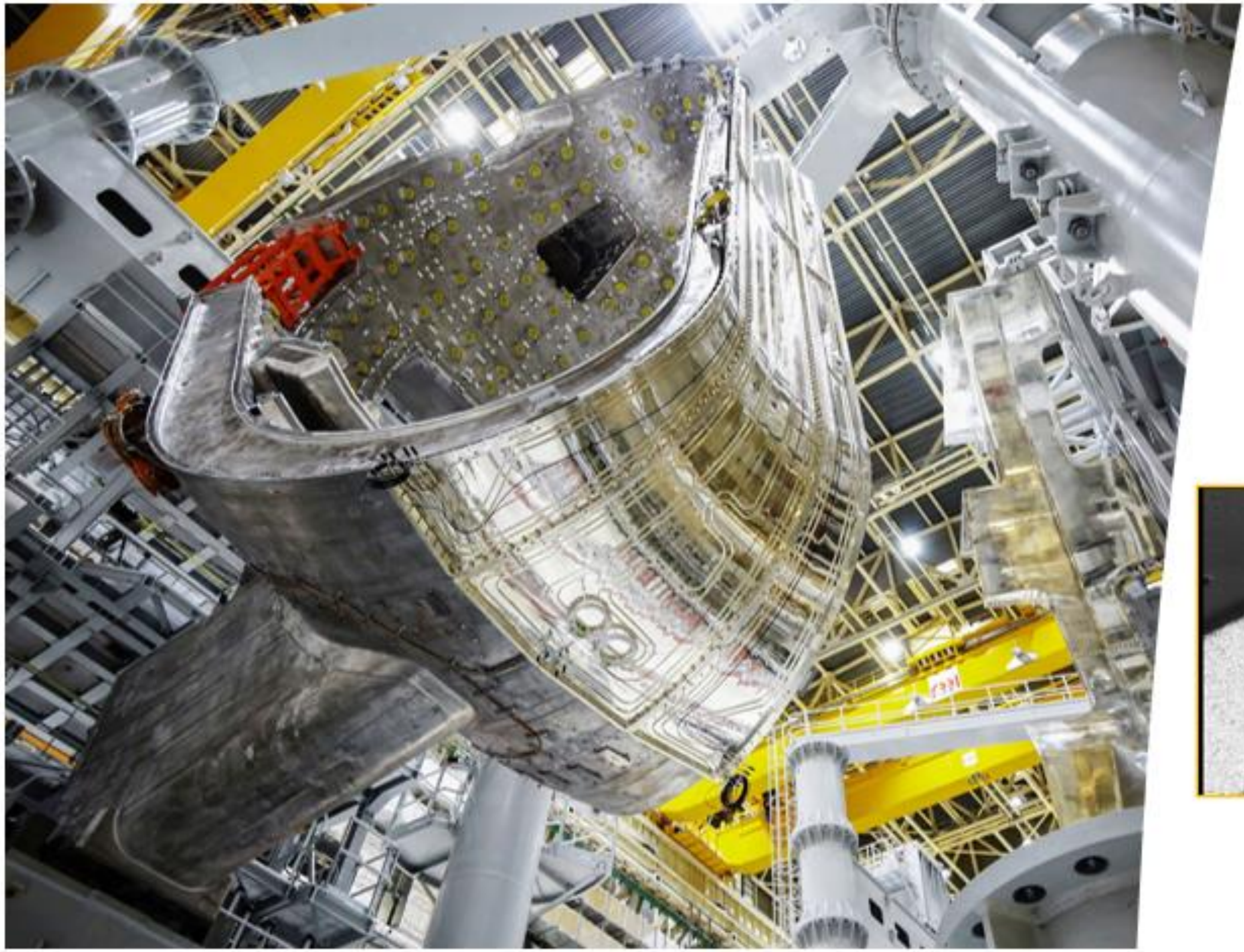
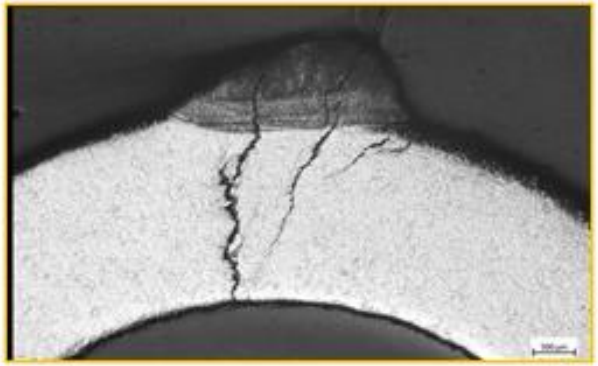
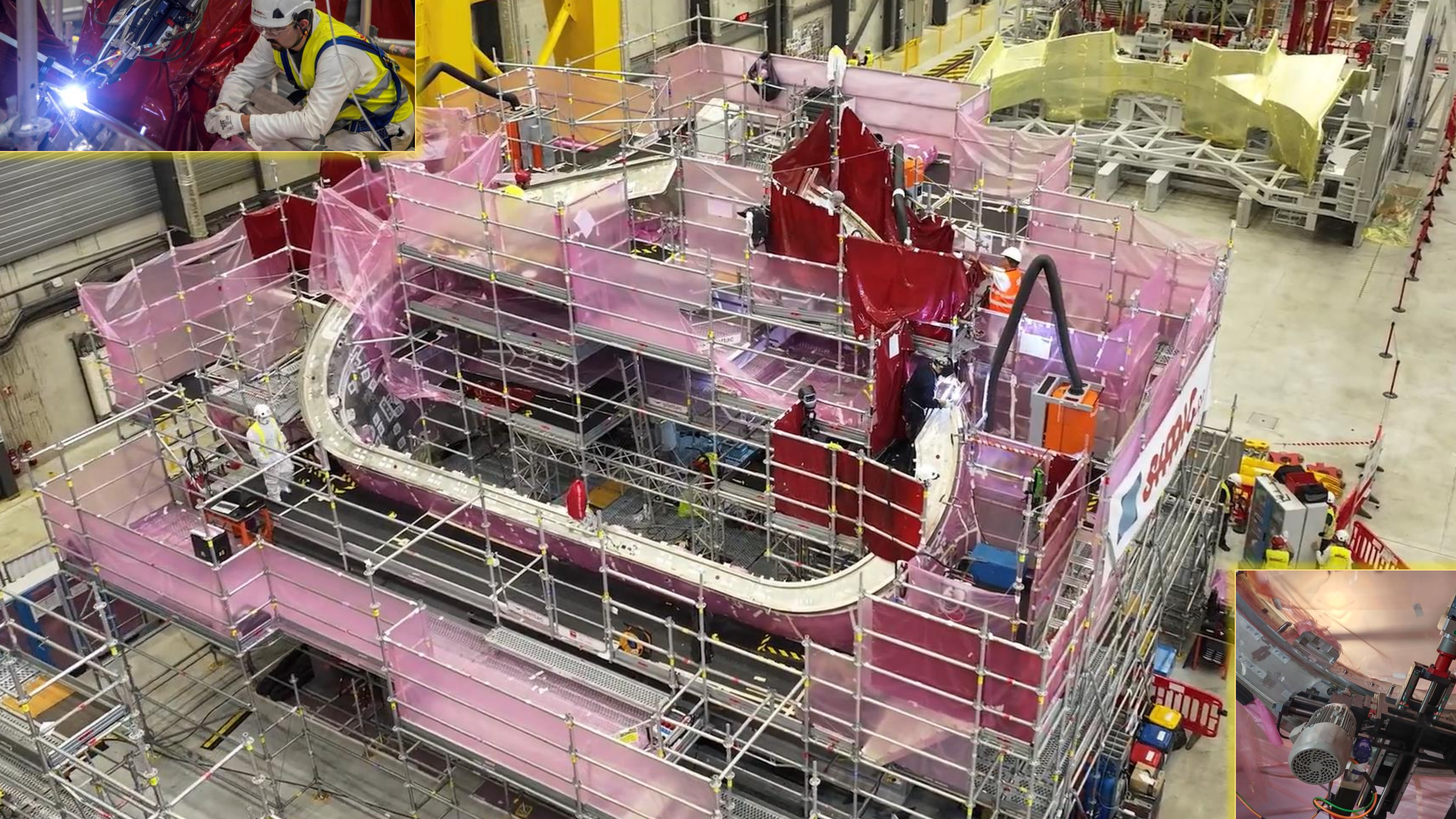


CHALLENGES OF FIRST-OF-A-KIND COMPONENTS

Leakage was also identified in thermal shield cooling piping due to chloride stress corrosion.



FEC 2023



VACUUM VESSEL THERMAL SHIELD REPAIR

- 2 mm panel machining to eliminate potential panel corrosion risk
- Replacement of corroded pipes with new 316L pipes
- Surface polishing with no Ag coating: surface roughness less than 0.1 µm – low emissivity at 80K
- VVTS repairs done for majority of sectors and well under control

See Noh et al @ wed 15 11:40

CENTRAL SOLENOID (CS) ASSEMBLY

Nb_3Sn, 13.5 Tesla, 42kA
6 modules, 1000 tonnes, 13m tall

- Fourth CS module stacked in January 2025.
- Fifth module just stacked
- Sixth module arrived 3 weeks ago.
- Seventh (spare) module repaired, awaiting shipment.

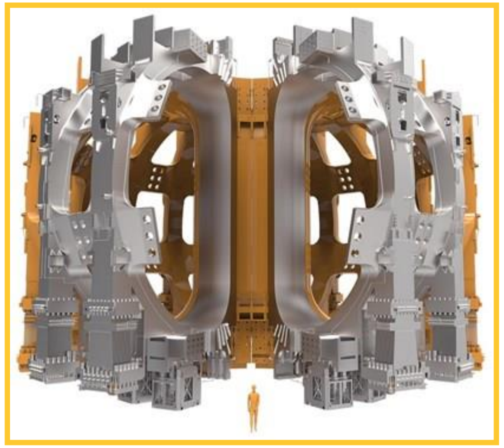
TOROIDAL FIELD (TF) COILS

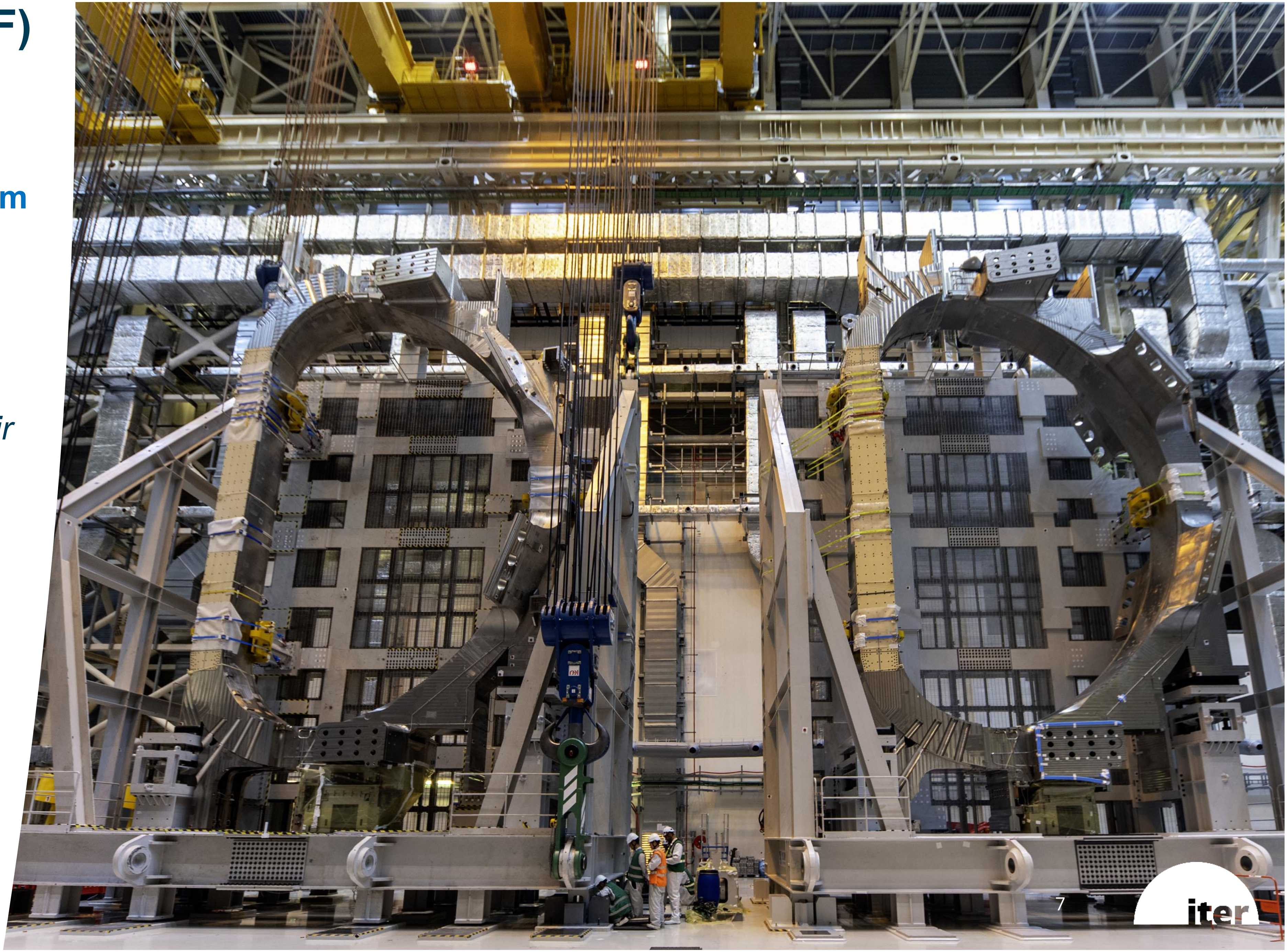
Nb_3Sn, 11.8 T, 68kA, 41 GJ
Each coil: 360 tonnes, 9x17m

Manufacturing of all 19 coils completed (including spare).

All coils delivered onsite (December 2023).

[Pictured: two TF coils on their "upending" assembly tools.]

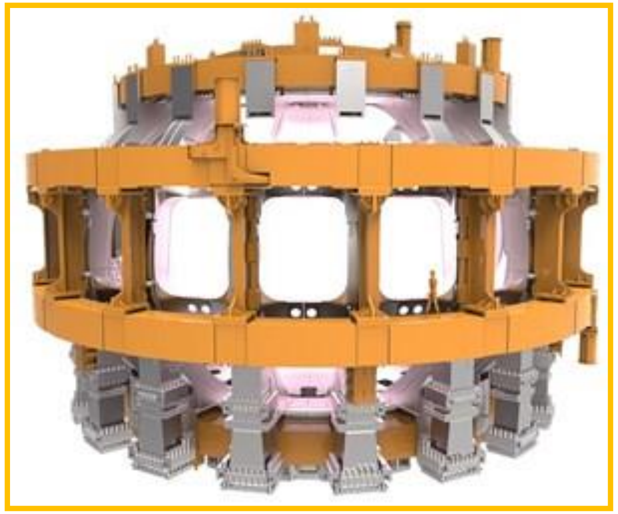




POLOIDAL FIELD COILS

NbTi, 6 Tesla, 45kA, 4 GJ
6 coils, 9–24m diameter, ~400 tonnes

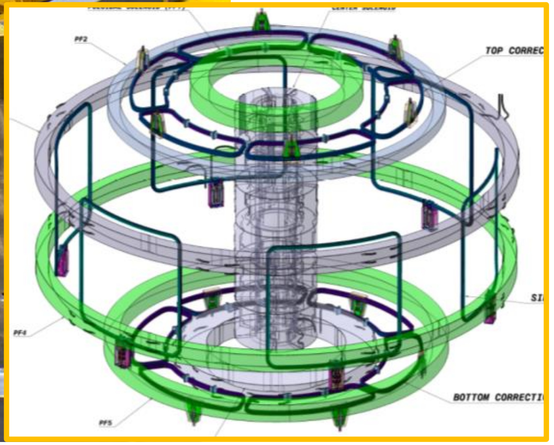
All PF coils completed and delivered on-site (March 2024).



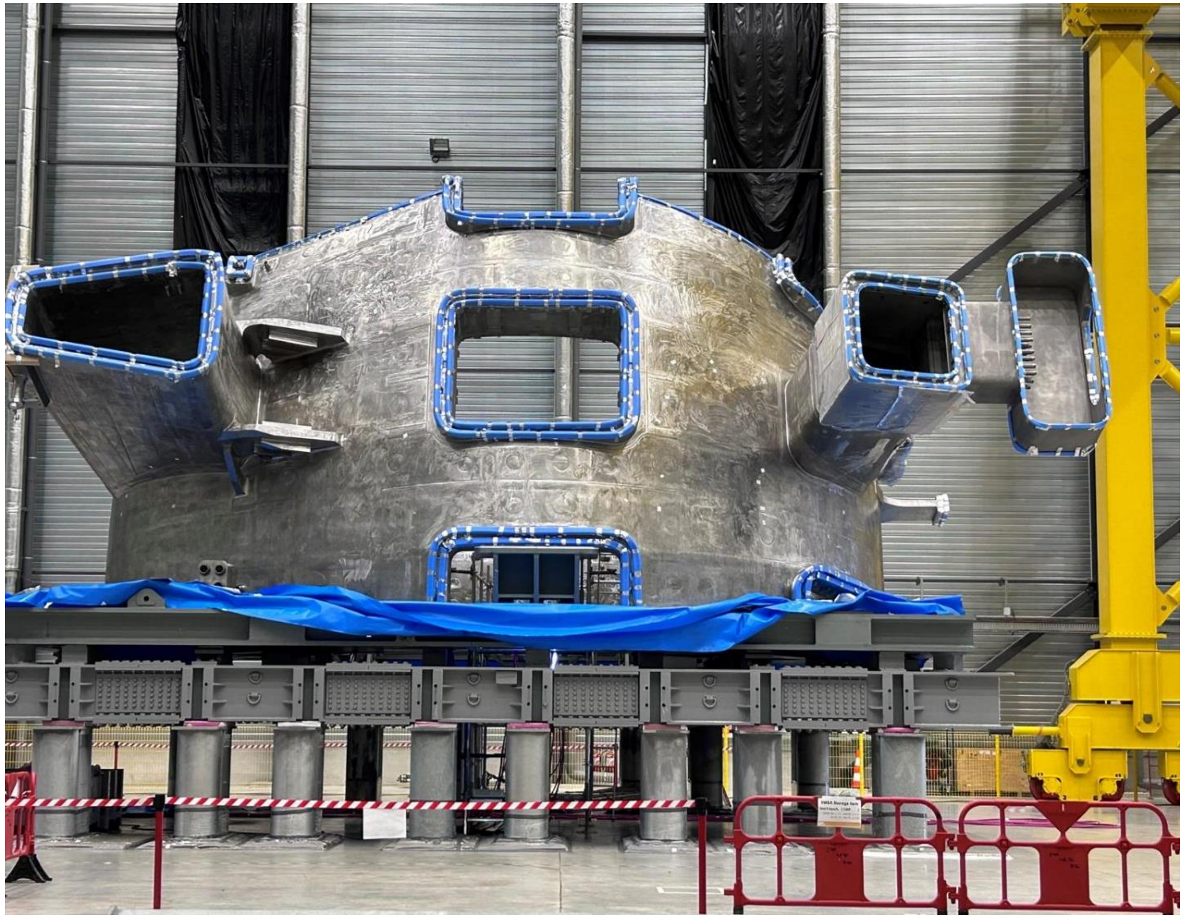
ERROR FIELD CORRECTION COILS

4 Tesla, 10kA, 10 MJ
Each 8m; total 60 tonnes

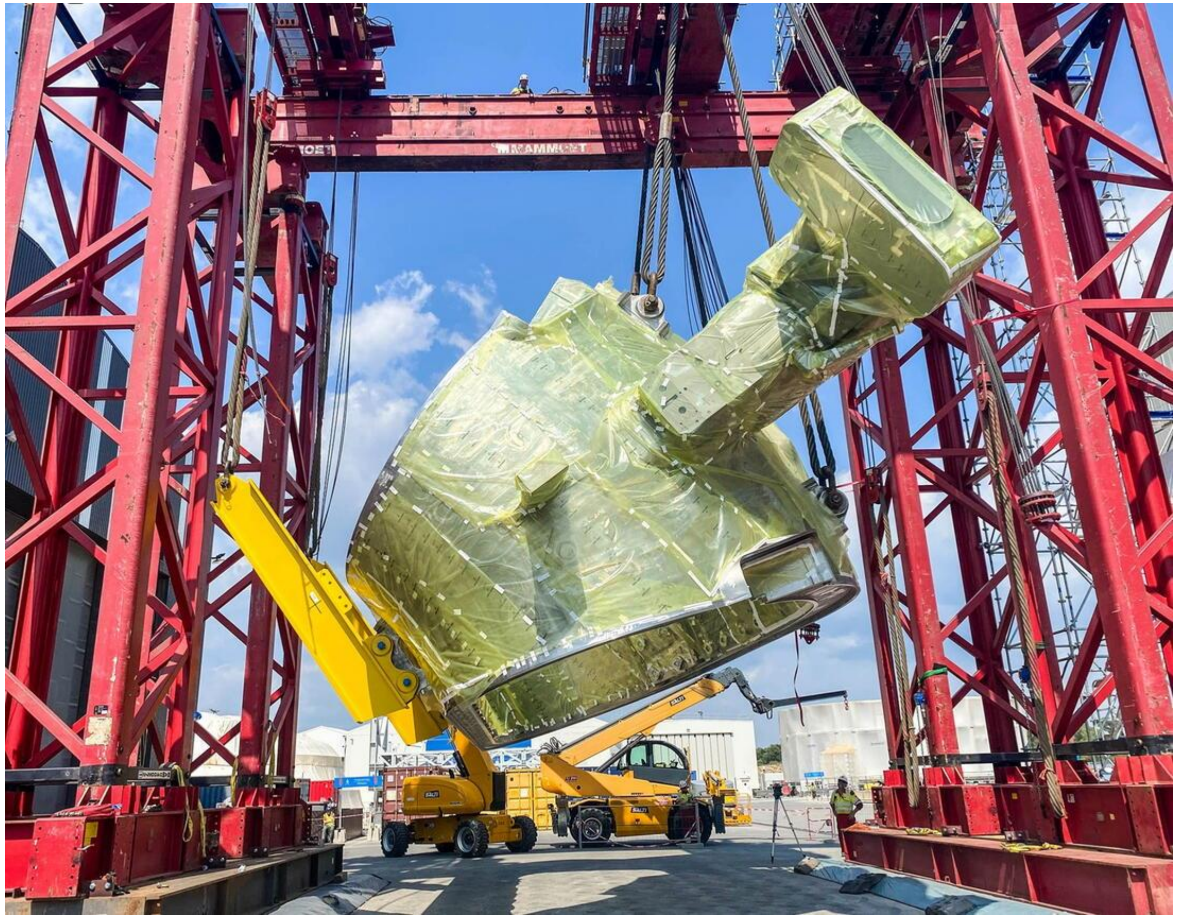
- 6 bottom correction coils installed.
- 6 top correction coils already delivered.
- 6 side correction coils: production completed.



VACUUM VESSEL SECTORS



Korea has delivered all four of its sectors.



Europe delivered its first vacuum vessel sector in October 2024. The second was delivered in May 2025 – shown here in June being rotated for repairs to the bevel joint surface.

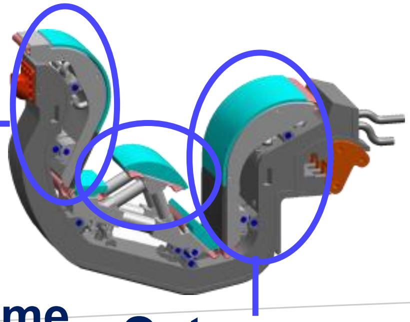
DIVERTOR

Divertor cassette body: series production ongoing

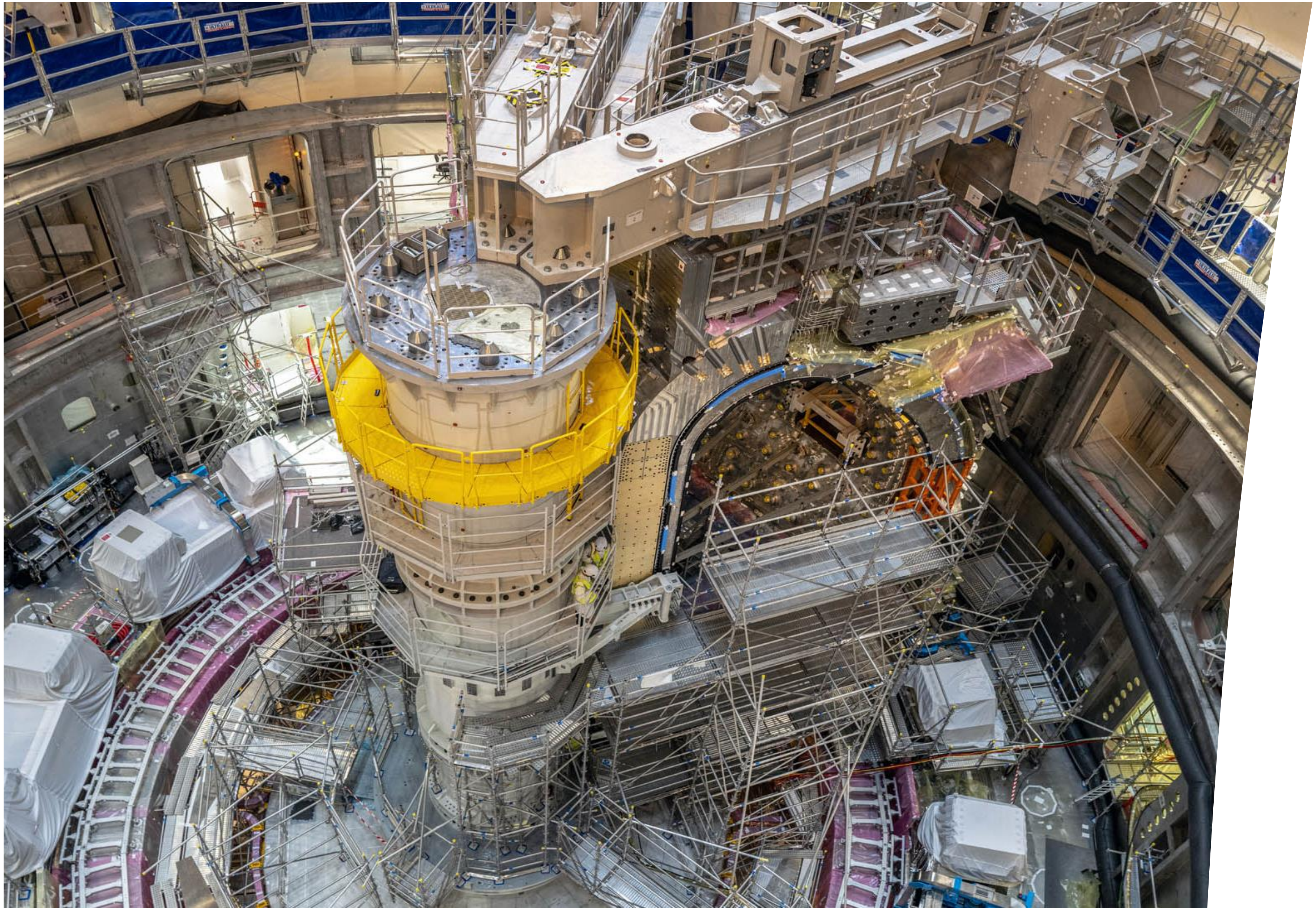
Dome

Inner vertical target

Outer vertical target



Qualification phase for all components **completed.**
Serial production by DAs is ongoing.
Contract for divertor cassette assembly integration awarded to consortium led by SWIP.



TOKAMAK MACHINE ASSEMBLY

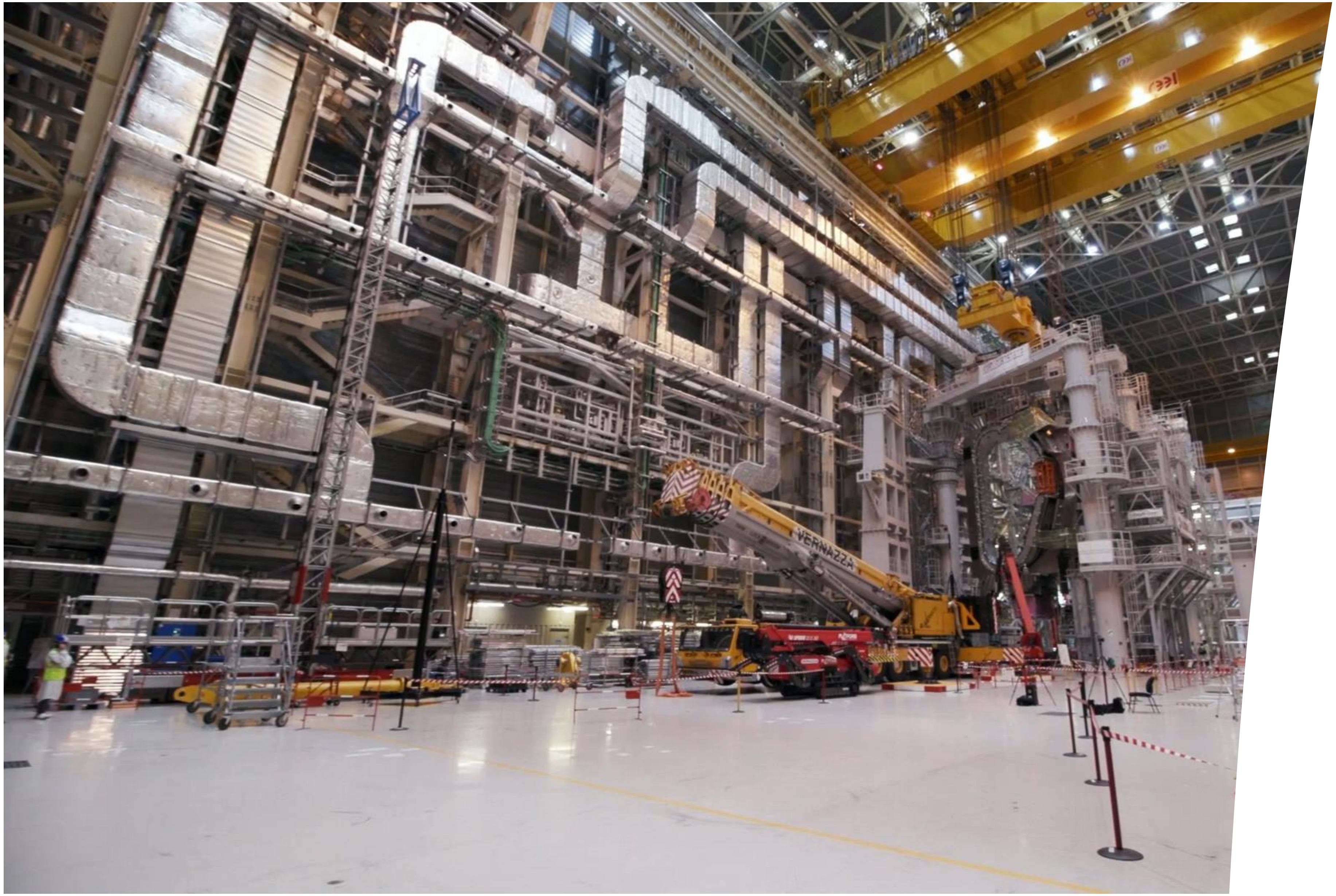
Assembly Contracts and organization reset in 2023.

Sector Module 7 sub-sector assembly completed, March 2025.

Then installed in Tokamak Pit, April 2025.

Sector Module 6 installed in the Tokamak Pit, June 2025

See J. Reich et al @ wed 15 11:20



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See J. Reich et al @ wed 15 11:20

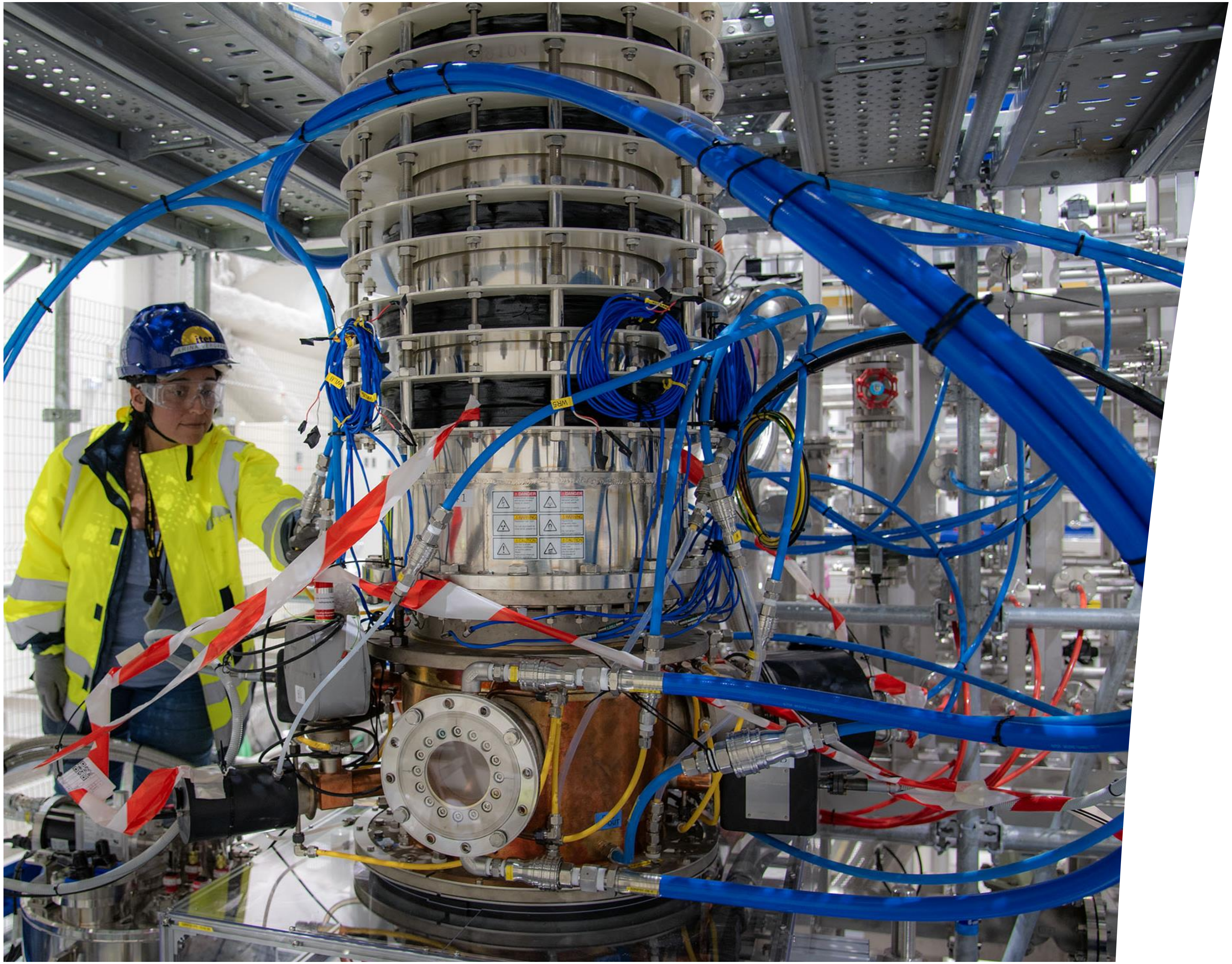
TOKAMAK MACHINE ASSEMBLY (cont.)

2 sector modules right now on the subassembly frames:

Sector 5

Sector 8

See J. Reich et al @ wed 15 11:20



ELECTRON CYCLOTRON HEATING

2.7-metre high gyrotron, delivered by Japan, was installed last month.

NEUTRAL BEAM HEATING

At the Neutral Beam Test Facility good progress has been achieved on two key parameters: Voltage holding and beam source current density.

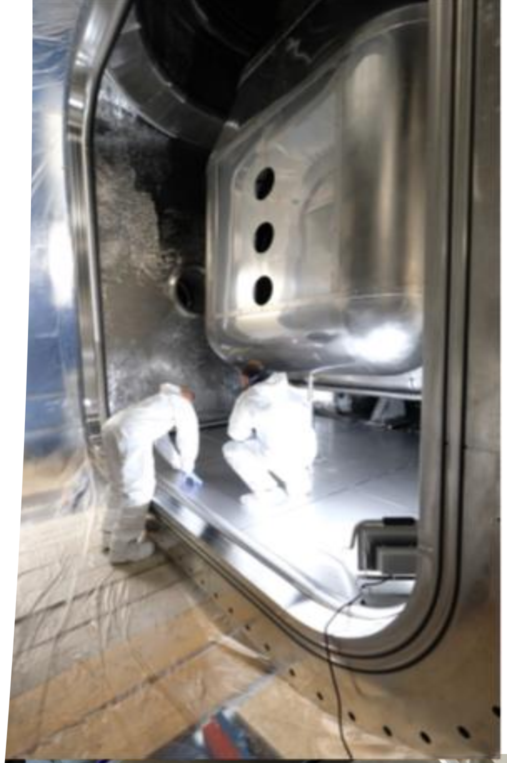
MITICA:

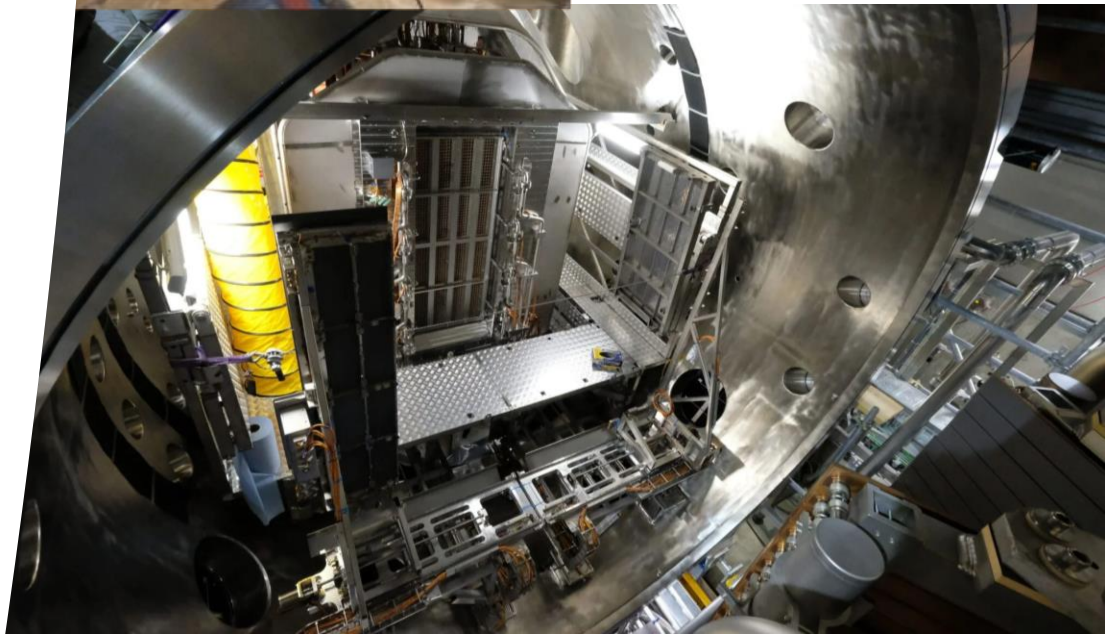
a record value holding of ~180 kV per stage was achieved on 3 stages of the system. In perspective, this demonstrates the feasibility to achieve > 910 kV on the full system.

(Target Values for H beam is 870 kV)

SPIDER:

(full scaled size of the ion source) demonstrated the scaling of beam current with applied RF power, up to 66% of required value.





See D. Marcuzzi *et al*. 15 Oct

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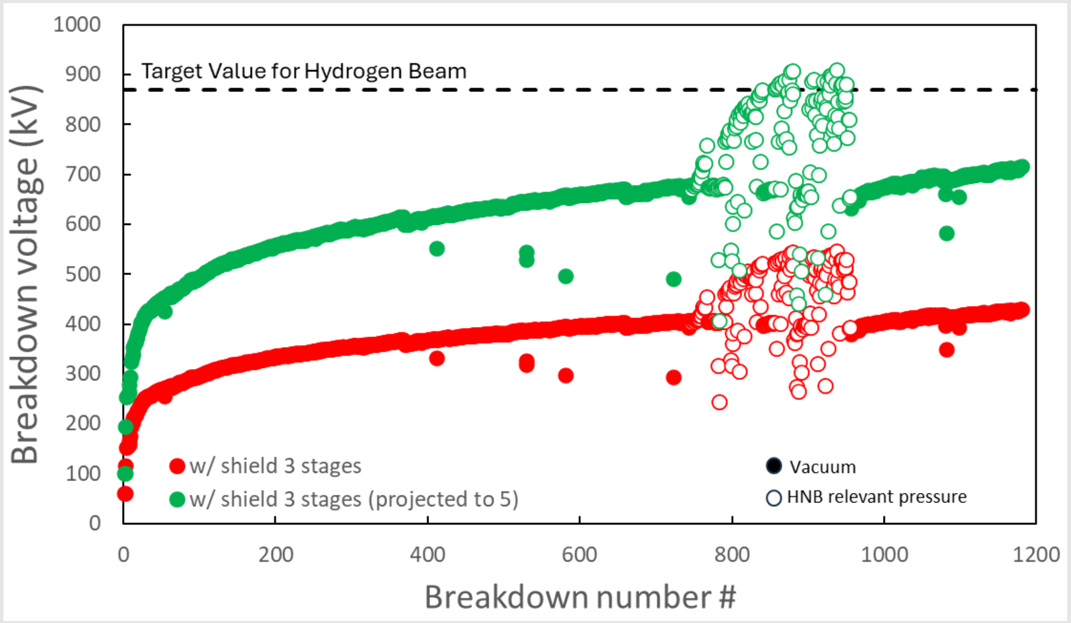
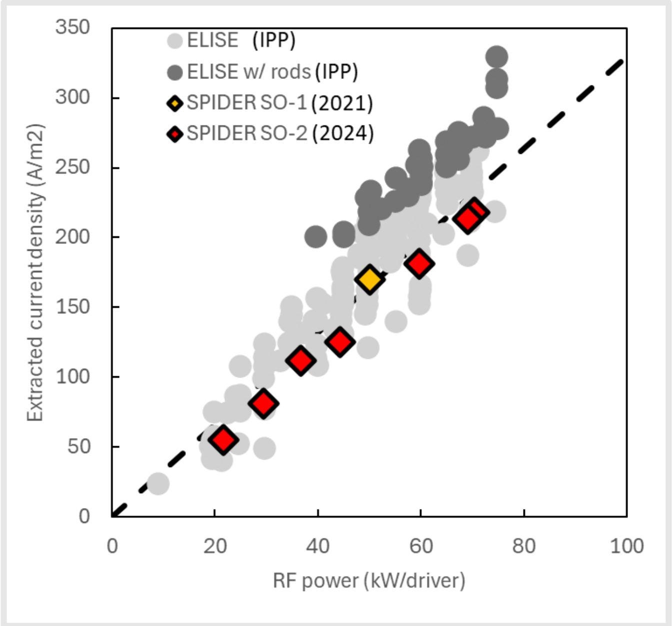


SPIDER



MAGNET POWER CONVERSION

Stage 1 AC/DC Power Converter systems from China:

- 14 PF Power Converters installed, with 89% of the low-voltage commissioning for these units completed.

Stage 1 AC/DC Power Convertor Systems from Korea:

- 18 TF/CS/VS1/CC Power Converters installed. For 3 of 18 units, low-voltage commissioning is completed.
- 3 sets of TF/PFCS/CC Master Control Systems installed, with 97% low-voltage commissioning completed

CRYOGENICS PLANT

Refrigeration: 75kW @4.5K

34 tonnes Helium inventory

40 MW_{elec} installed power

Heat Load removal through HVAC ≈ 2.55 MW_{th}

Commissioning largely completed.

Helium liquefaction first achieved in December 2024.

NEW MAGNET COLD-TEST FACILITY

Cryostat arrived at ITER on 4 October

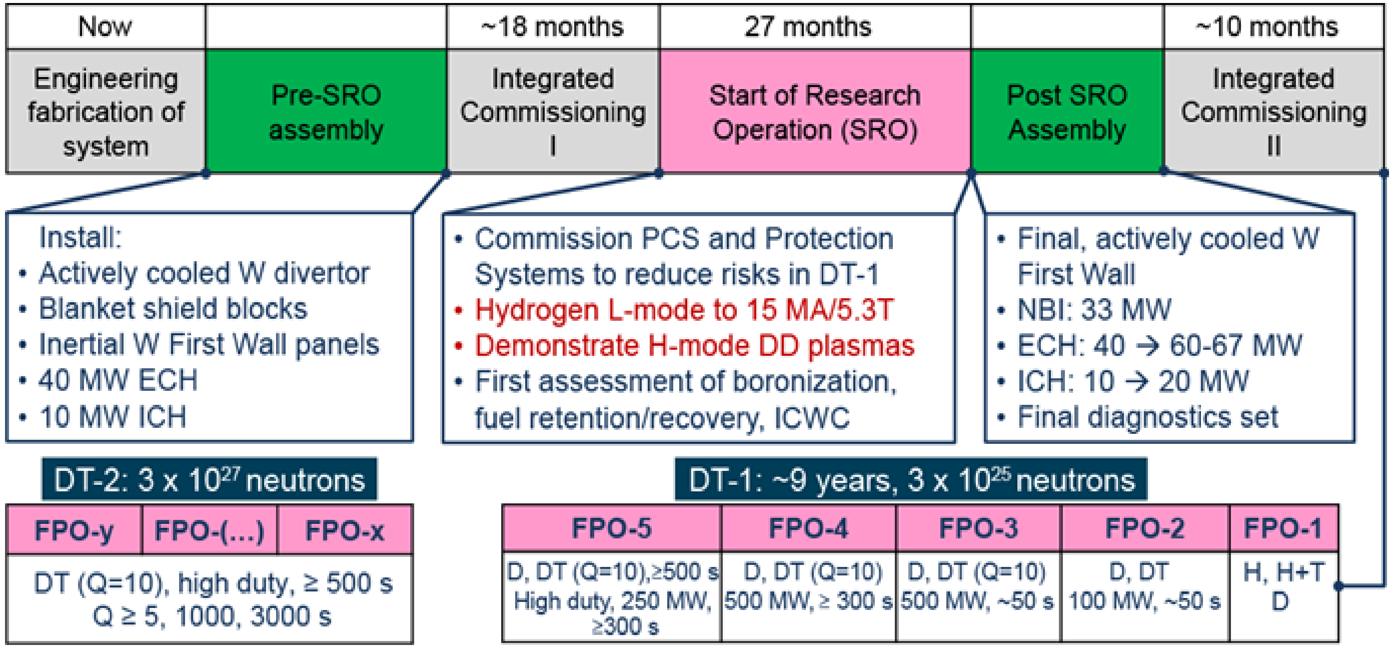
Cold testing at operating temp. (4K) has so far been limited to Central Solenoid Modules.

The Magnet Cold Test Bench will allow a few TF coils and PF1 to be tested at nominal current before integration, by testing:

- Coil and joint performance
- High voltage ground insulation at different T
- Quench protection systems
- Fast Discharge – cryoplant integration
- Coil thermohydraulic performance

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



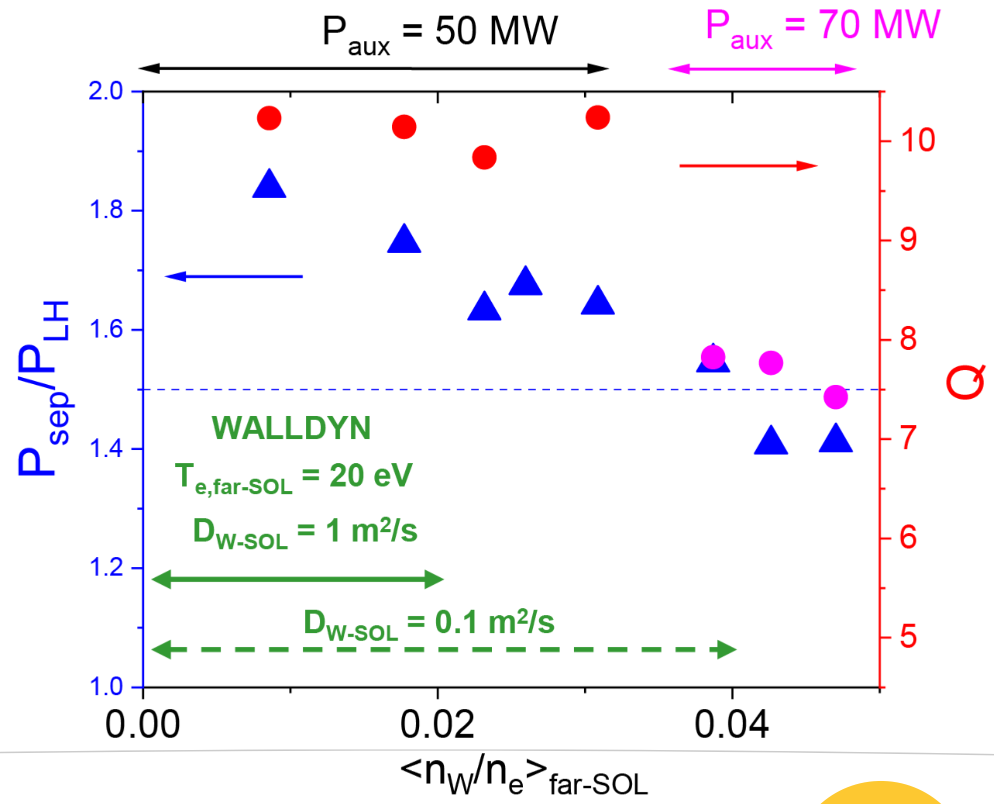
R. A. Pitts et al. Nucl. Mater. Energy **42** (2025) 101854
A. Loarte et al. Plasma Phys. Control. Fus. **67** (2025) 065023

See S.W. Yoon *et al*. 15 Oct @11:00

Change of first wall material (Be → W)

- Major gains: reactor relevant, much lower erosion and T-retention, no toxicity, much higher resilience to transients → easier disruption mitigation
- Potential risk: increased core W concentrations and possible plasma start-up issues → increase ECH heating by 40-47 MW and new boronization system

- State-of-the-art, high-fidelity codes and end-to-end scenario modelling supported by experiments on ITER Members' facilities used to quantify and mitigate risks to low/medium level
- Research Plan supported by strong programme in Integrated Modelling in collaboration with fusion community → drive to make ITER Integrated Modelling and Analysis Suite (IMAS) open-source (https://github.com/iterorganization) → validation on current devices essential (needs data mapping)



See A. Loarte *et al*. 15 Oct @11:20; M. Schneider *et al*. 15 Oct @17:30; S. D. Pinches *et al*.16 Oct @14:00; S.H. Kim *et al*. & F. Poli *et al*.17 Oct @14:00;F. J. Artola *et al*. 18 Oct @08:30

ITER Disruption Mitigation System

- 27 Shattered Pellet Injectors with H, H/Ne, Ne cryogenic pellets
- Final Design Review approved Dec. 2024 → now passing to manufacturing phase
- Ready from start of SRO
- Massive international collaborative effort through DMS Task Force led by IO

See S. Jachmich *et al*. 17 Oct @14:00

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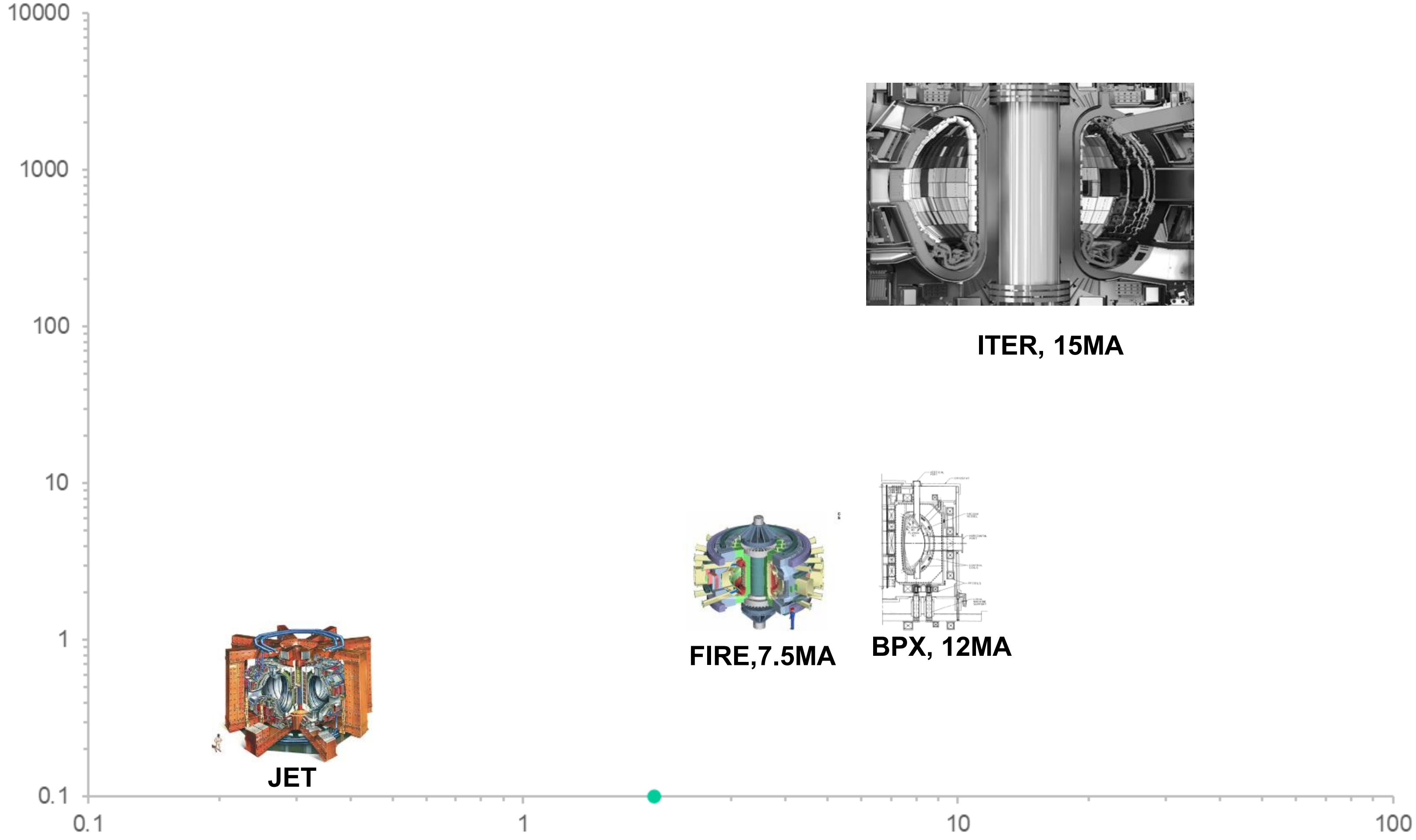
Q1: Why R~6?

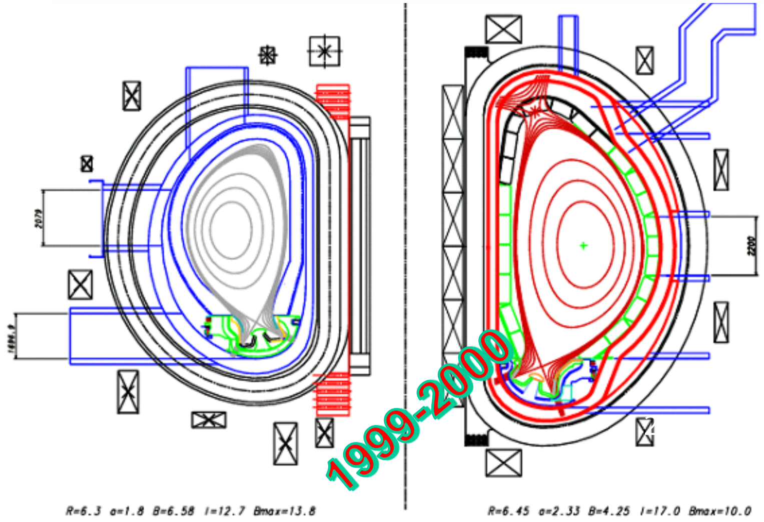
- nTt with conservative assumptions -> 15MA
- Thermal equilibrium of structures
- Shielding blanket sized to operate for long pulses AND allowing for potential breeding (>1.2m between magnet and plasma edge)



Q2: and what if…we designed ITER today?

- Nothing fundamentally new in confinement
- Power flux still an issue
- Still need a FW and a breeding blanket would require >1,2m
- And what about Field? Would it change if we would use HTS?
- Nb3Sn can work at fields >>12.5 T
- In ITER Nb3Sn takes only 4% of inboard cross section.
- Already in 1990s was well understood: For a burning plasma experiment, lasting a few seconds, that may work… i.e. CIT, BPX, CIT, FIRE, Ignitor are past design which, even if not at 15MA, were intended for that purpose (e.g. BPX, 1992, ~JET size, Ip~11MA) … but in transient conditions.

- ITER's field is not chosen on some cliff edge J in magnet at 12.5T…in 1999-2001 high(er) field version of ITER. Marginal reduction of size, albeit increase in cost and power flux.



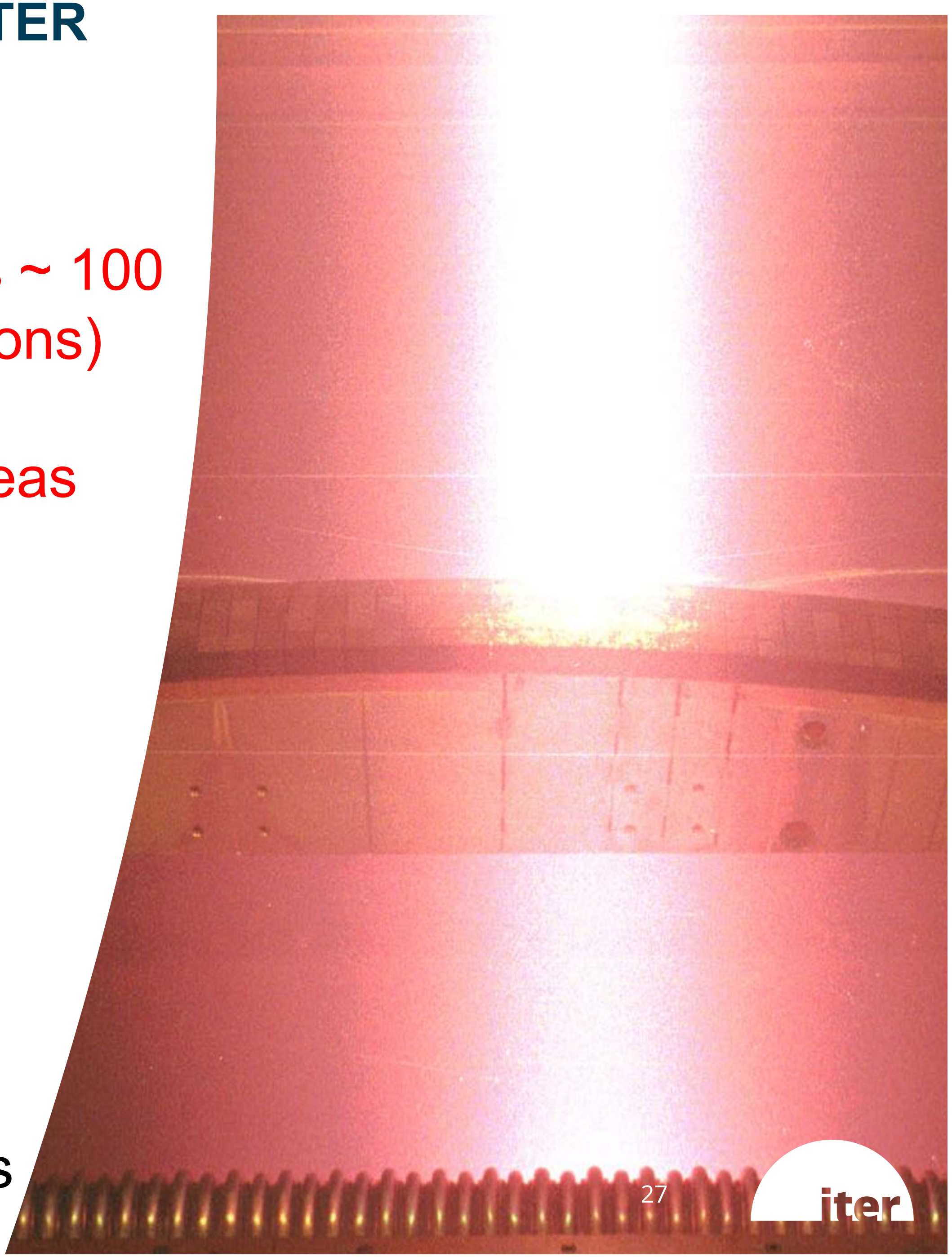
Q3: what about the cost? Not just size.. But largely driven by:

- Organizational complexity and political compromises
- Technical complexity
- Escalation of requirements
- FOAK issues

- Could we do it faster, and cheaper? Yes
  - Avoid problematic sharing of deliveries
  - Early industry involvement: Engaging suppliers during the design phase ensures manufacturing processes are reflected in design choices.
  - Appropriate quality grading: Over-specification should be avoided to prevent unnecessary costs.
  - Practical loading conditions: Mechanical and thermal loads (and stresses) must be kept within ranges that do not force overly complex solutions, tolerances, material specs, etc..
  - Simplified system interfaces, and control them well: Avoiding tightly packed or over-interdependent subsystems reduces costly cascading design changes.
  - Assembly-aware design: Allowing adequate space for assembly and maintenance prevents expensive complications; “smaller” is not always cheaper.

Q4: FUSION'S REMAINING CHALLENGES beyond ITER

- Cost
- Surface Heat Flux management
  - Heat flux is far from uniform - peaking factors ~ 100
  - Transients (MHD instabilities, ELMs, Disruptions)
- Materials resistant to extreme conditions
  - Intense flux of high-energy neutrons, over areas with enormous surface heat flux
  - Erosion
- RAMI, e.g.
  - Remote handling for maintenance
  - Reliability against Leaks
- Tritium breeding and fuel cycle
  - Lithium 6, large amounts needed
  - Breeding challenging, even with ~1m blanket
  - Small burn %, large circulation
- Overall efficiency, due to large circulating powers
- Current Drive in Tokamaks



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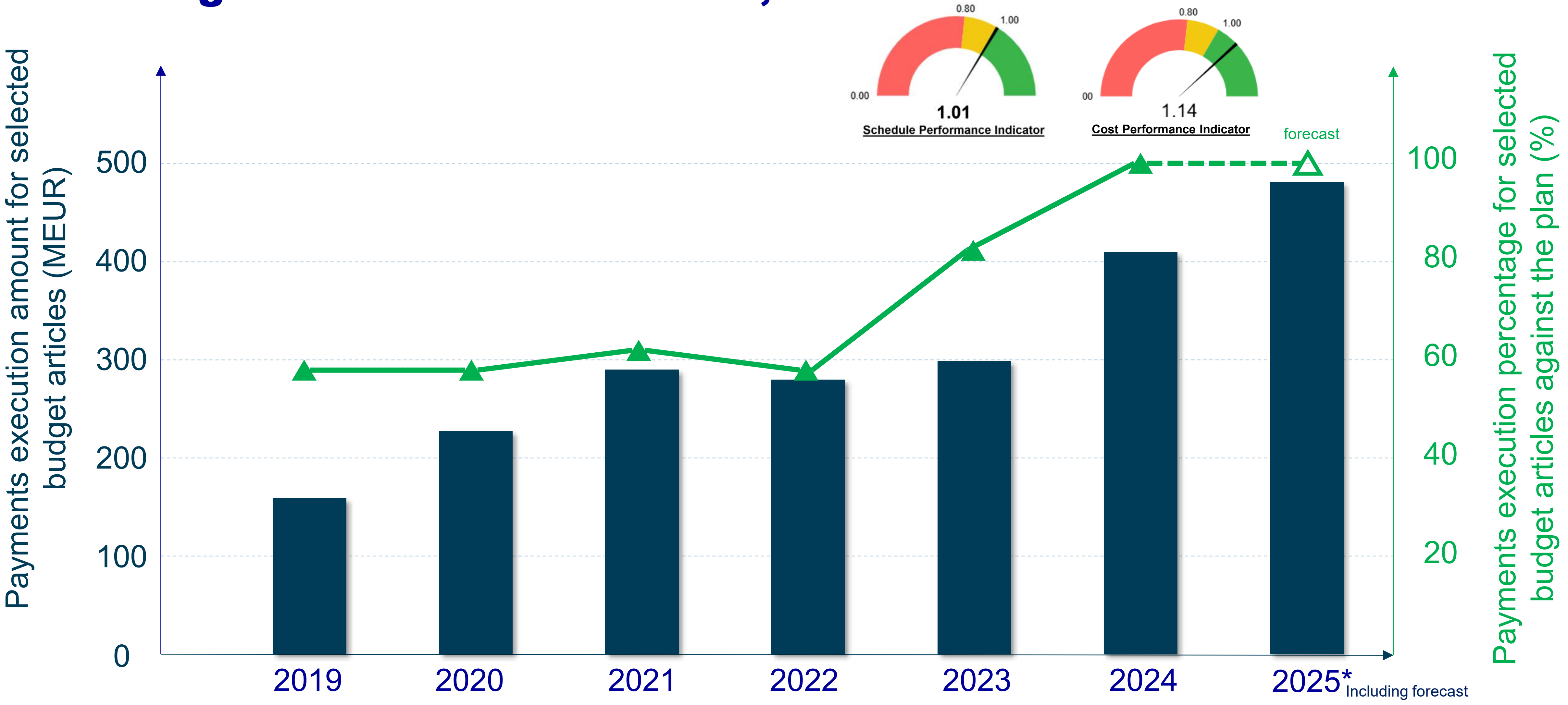
NEAR-TERM RETURN ON THE ITER INVESTMENT

- ITER as learning ground for fusion workforce
  - Unique opportunity to learn the realities of complex assembly
  - ITER is a common resource for the world fusion community also now
- Supply chain: while ITER’s approach for distributed contribution of components is challenging, it means Member companies gain unprecedented expertise: *a de facto global supply chain for fusion*
- Private sector fusion engagement
  - Access to ITER documents
  - Open-sourcing major software
  - Participation in ITPA committees
  - Exchange of visits

Conclusion: FROM THE TURNAROUND YEAR IN 2023, THE ITER PROJECT PERFORMED AT RECORD RATES OF EXECUTION IN 2024

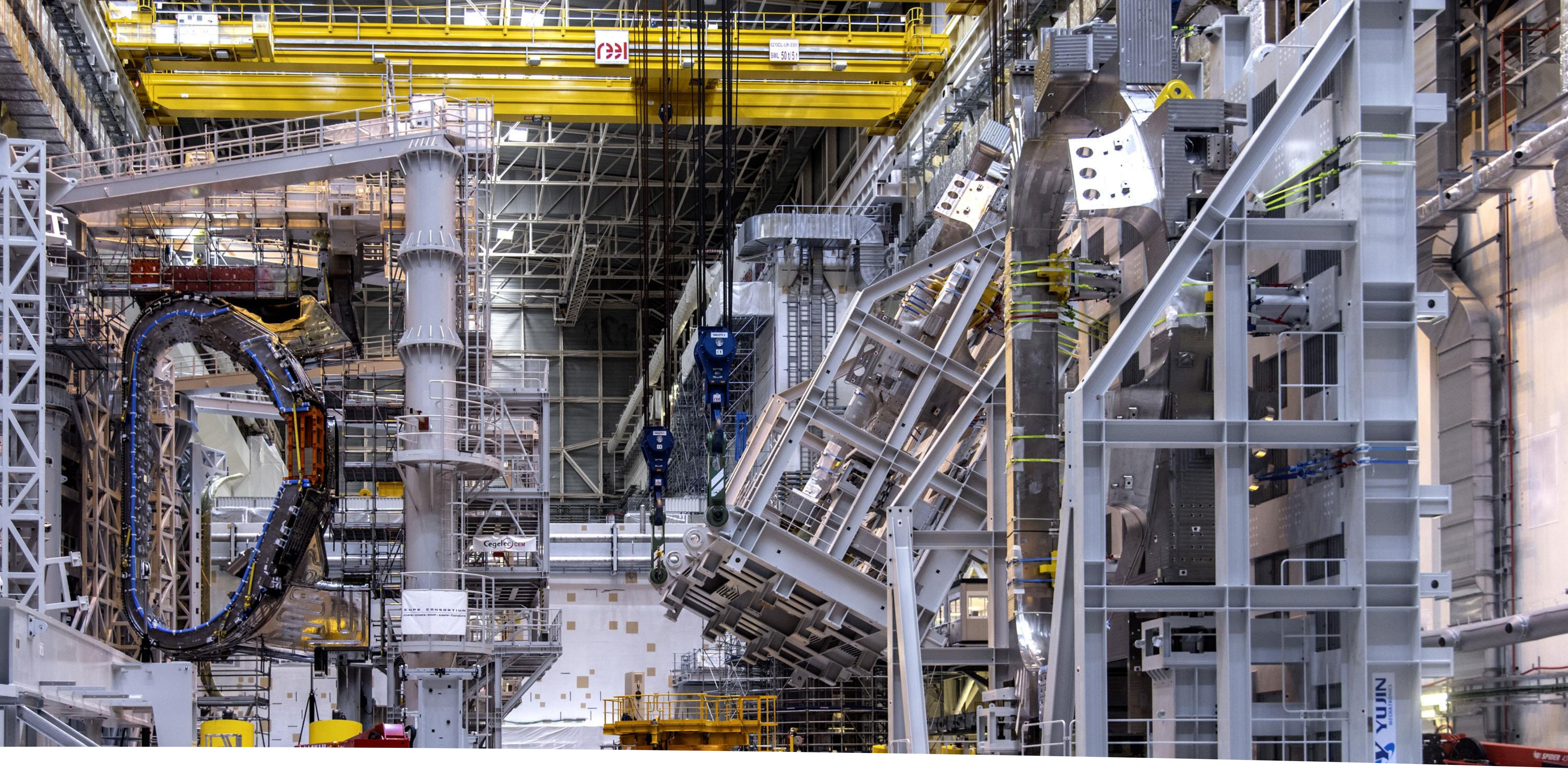
- Major restructuring of organisation
- Recovery of trust with the French Nuclear Regulator, and initiation of important simplifications ;
- Restructuring of assembly contracts
- Repair of components;
- Development of the new Baseline, with many new concepts therein;
- Improvement of project and design control processes;
- …while achieving record (>100%) execution for construction
  - SPI = 1.01
  - CPI = 1.14

In 2025, ITER will again achieve 100% on planned Construction capital growth related activities, with SPI=1.01 and CPI=1.14



Note: Construction Related articles includes A111 (Direct Investment), A112 (Test Blanket Module) , A321 (General Services), A323 (Equipment)*

Schedule Performance Indicator: Earned Value / Planned Value (per defined in the Baseline 2024)
Cost Performance Indicator: Earned Value / Actual Cost



Thank you for your attention

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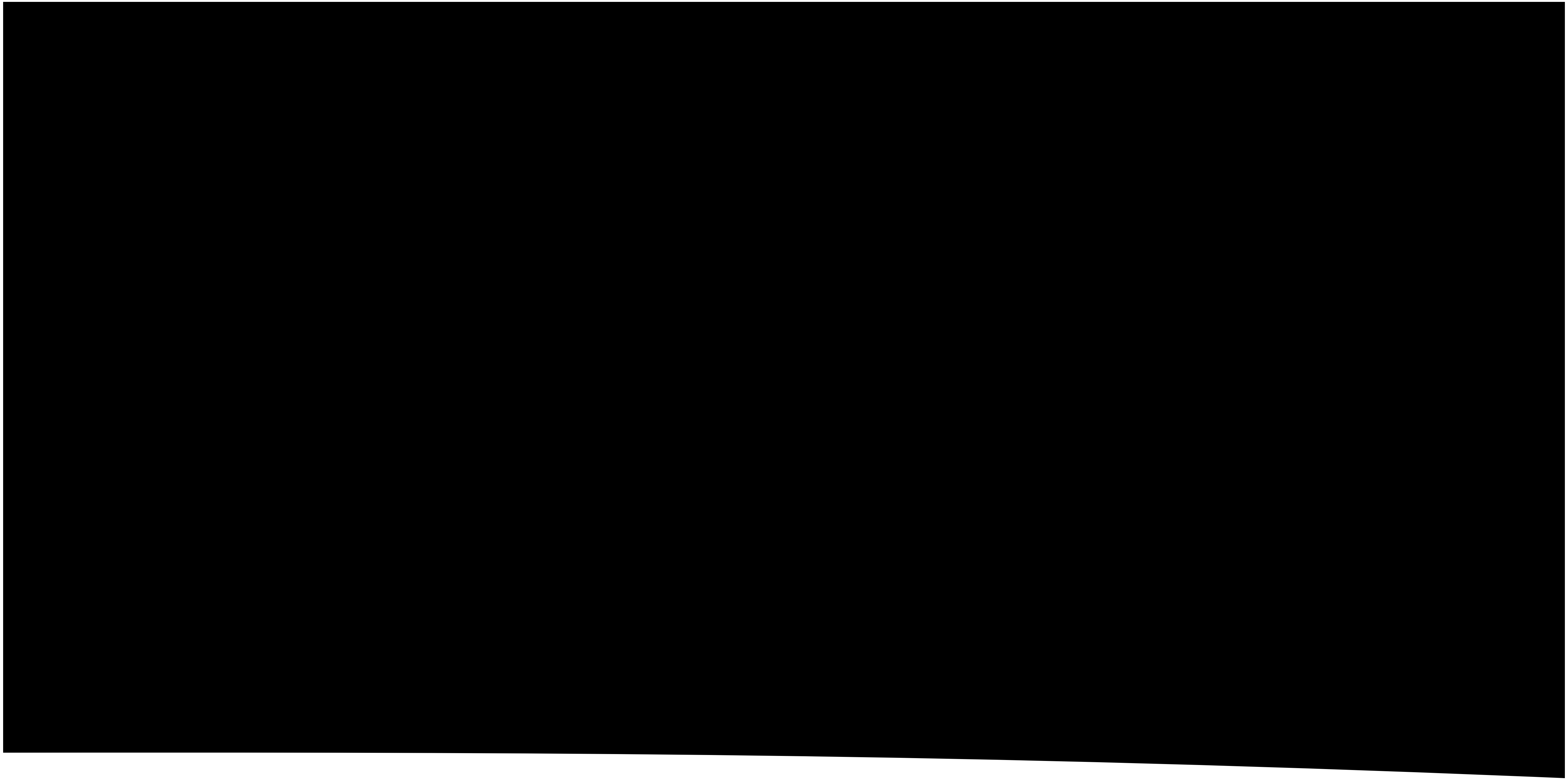

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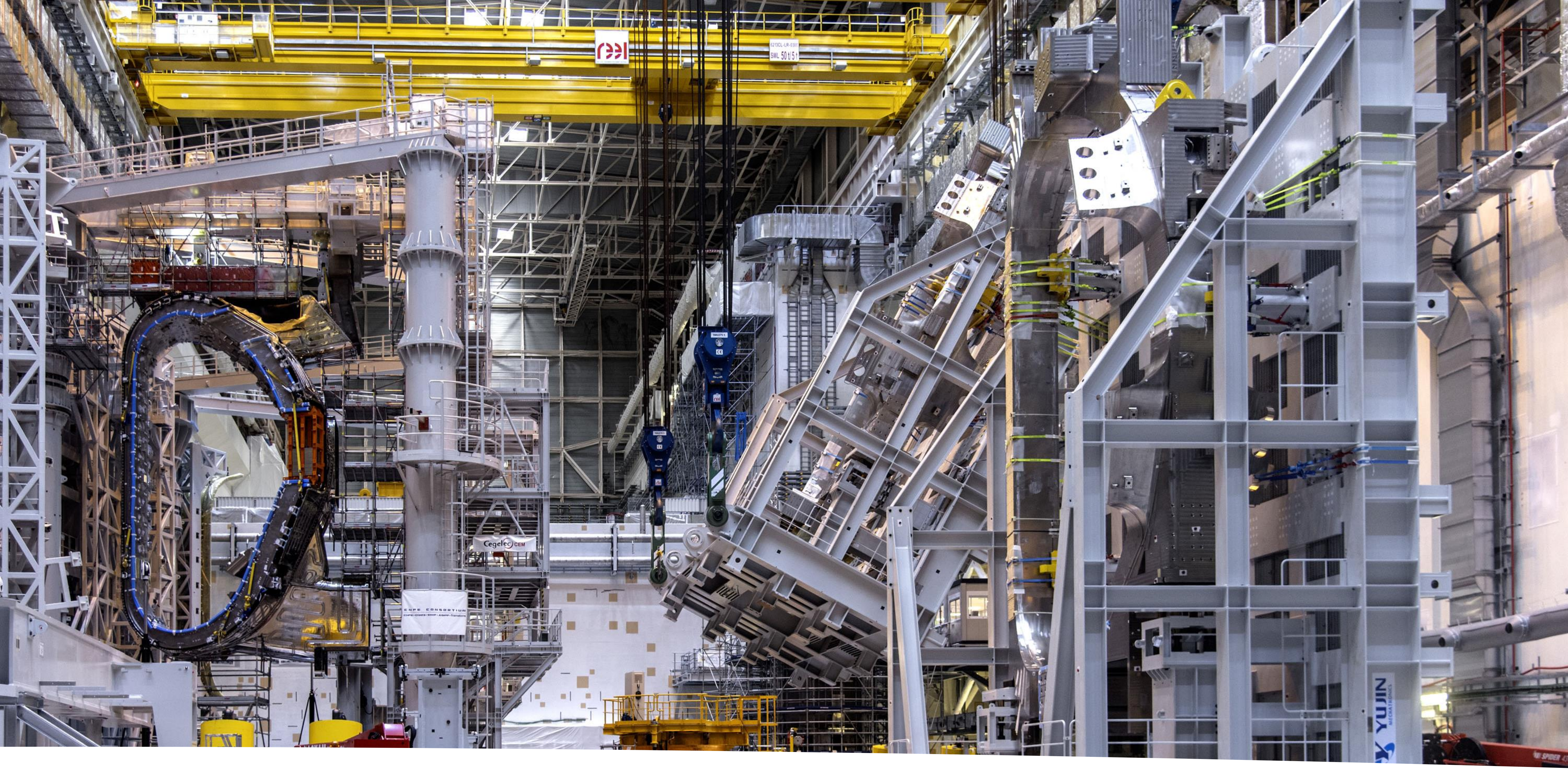

Spare slides

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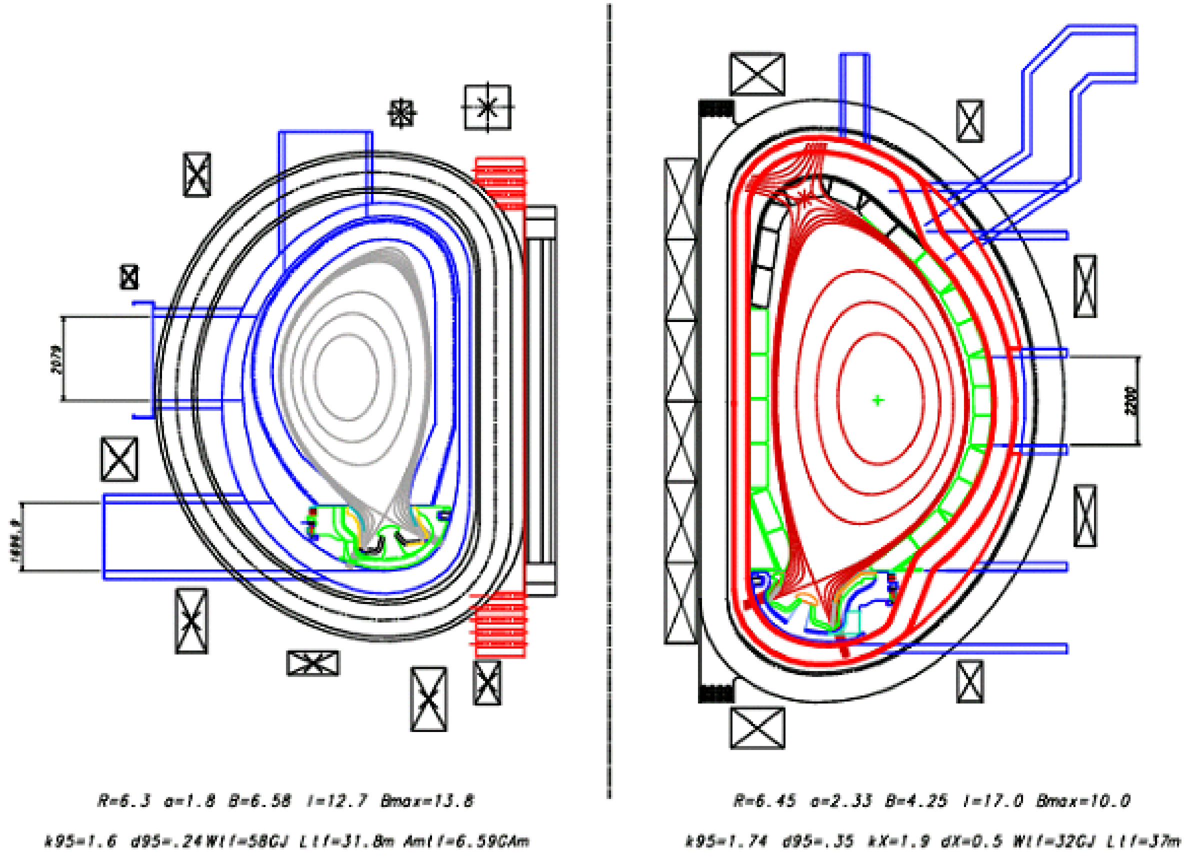
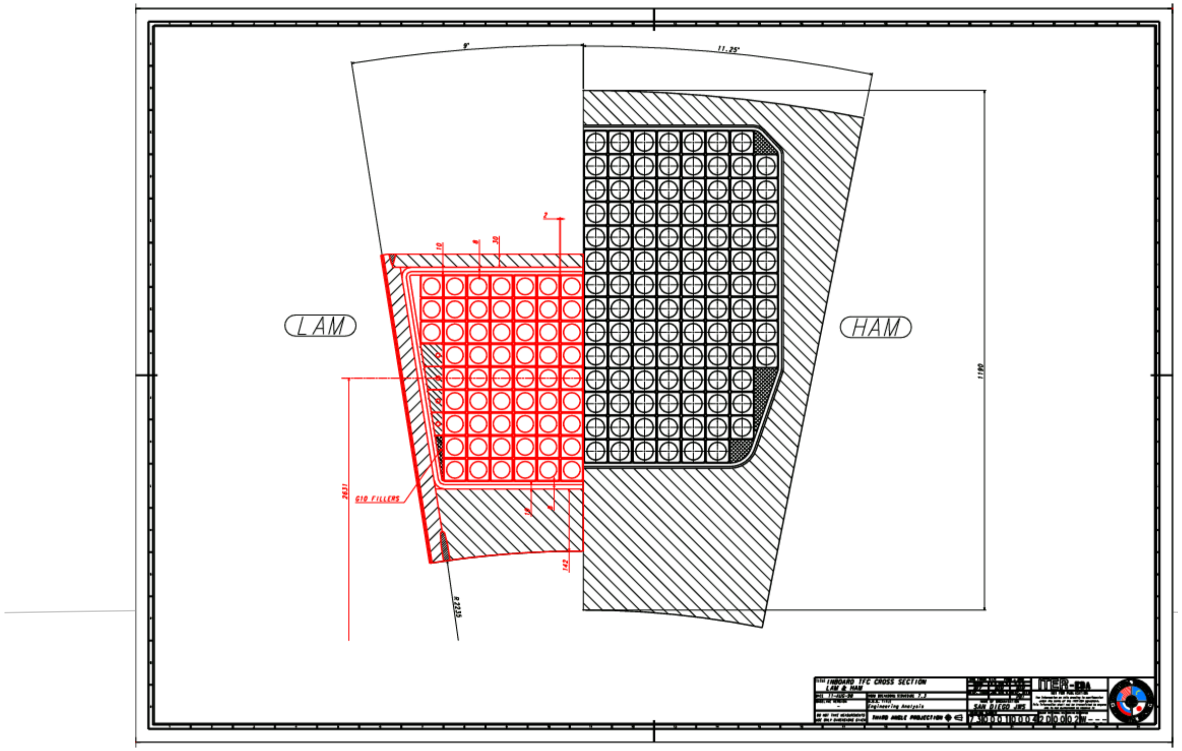
china eu india japan korea russia usa

Infact…Nb3Sn allows higher field than in ITER

Studies performed in 1999-2001 changing field and aspect ratio

Higher field device had serious issues of controllability, disruption loads, power flux





The design process undertaken for ITER

- A systematic use of a System Code approach was (regrettably) not used in ‘98 design due to too many design changes versus the previous design (CDA)

- Redesign for reduced scale ITER was useful as the whole system was re-optimised once a deep appreciation of all detailed problems was present: A systematic approach
  1. Conceptual design, problems (dimensioning loads) identification
  2. Detailed Solution of main problems, focussing of R&D and engineering and physics
  3. Quantitative Appreciation of system level design drivers
  4. System code implementation and parametric analysis
  5. Identification of a few design options
  6. Development of design options in detail
  7. Selection

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Tokamak Design: Machine parameters

- **For a SC Tokamak, given:**
  - **Desired Plasma "performance": Q, burn time, # of shots**
  - **Plasma Boundary conditions: q, n_{gwmax}, β_{Nmax}, κ, δ, H_H**
  - **Physics Criteria: τ, n_{gw}, P_{LH}, Beta**
  - **Engineering Criteria: Stress, loads, SC criteria, times and solutions for maintenance, Access to Plasma (diags, H&CD), Nuclear criteria, Design solutions…**

- **Only Aspect ratio (or Peak Field in magnet) is left 'free'**
  - **However, allowable κ and δ are function of R/a for divertor space, plasma shape and position control. Access to plasma is function of ripple requirements and R/a**
  - ***NB:In the case of Steady State tokamaks also the safety factor may be an optimisation parameters.***

- **A System Code is normally used to study options combining physics rules with engineering design knowledge. It can only be used if a more detailed design of a particular type of machine has been done and the experience / knowledge has been implemented**

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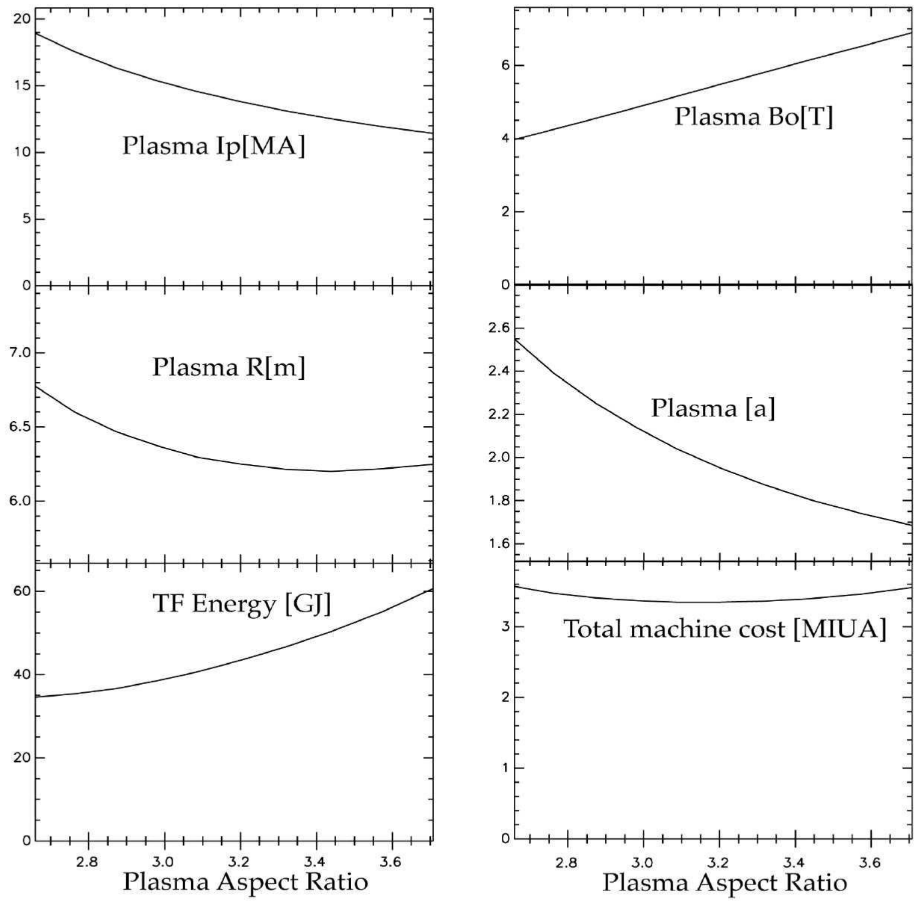
Typical results from the System Code Study

- **The main machine parameters and the cost change with increasing aspect ratio in the following way:**
  - **The toroidal Field, the Magnetic Energy increase with Aspect Ratio**
  - **The minor radius and the Plasma Current decrease with Aspect Ratio**
  - **However, the cost of the machine stays ~constant over most of the Aspect Ratio range investigated**



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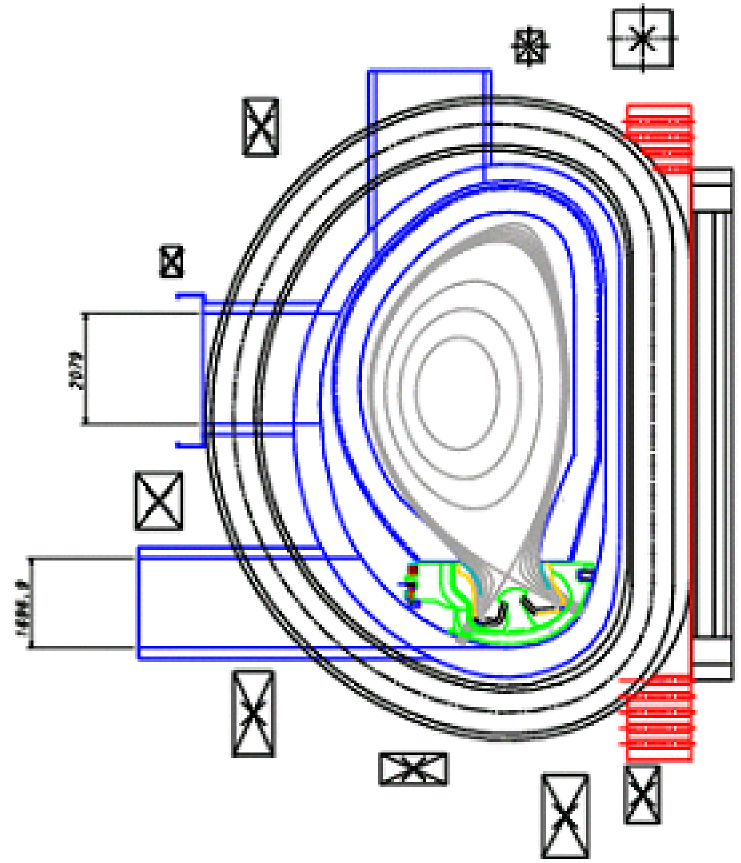
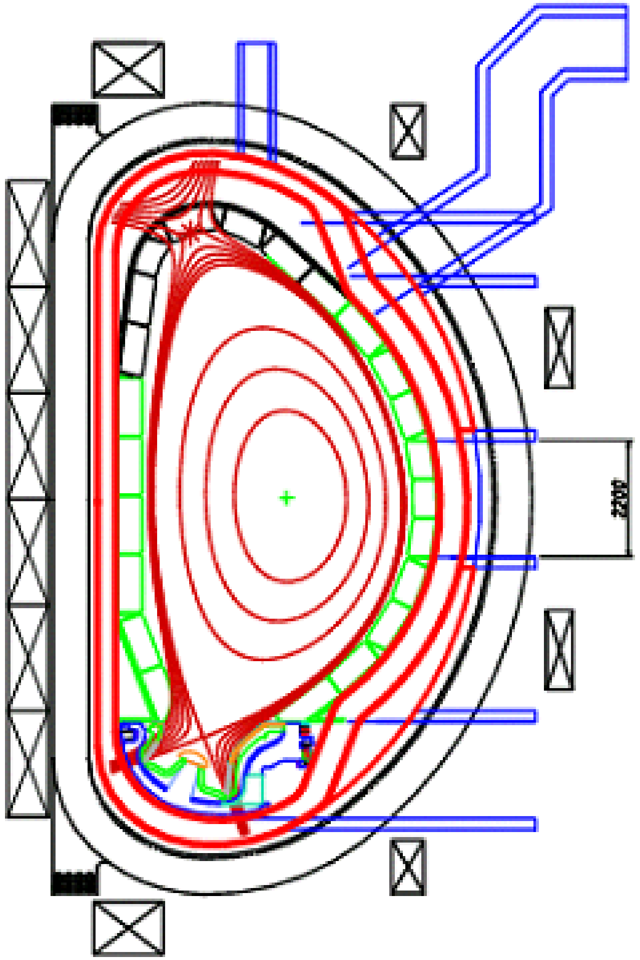
Machines with different R/a – Elevation View



R=6.3 a=1.8 B=6.58 I=12.7 Bmax=13.8

k95=1.6 d95=.24Wtf=58GJ Ltf=31.8m Amtf=6.59GAm



R=6.45 a=2.33 B=4.25 I=17.0 Bmax=10.0

k95=1.74 d95=.35 kX=1.9 dX=0.5 Wtf=32GJ Ltf=37m

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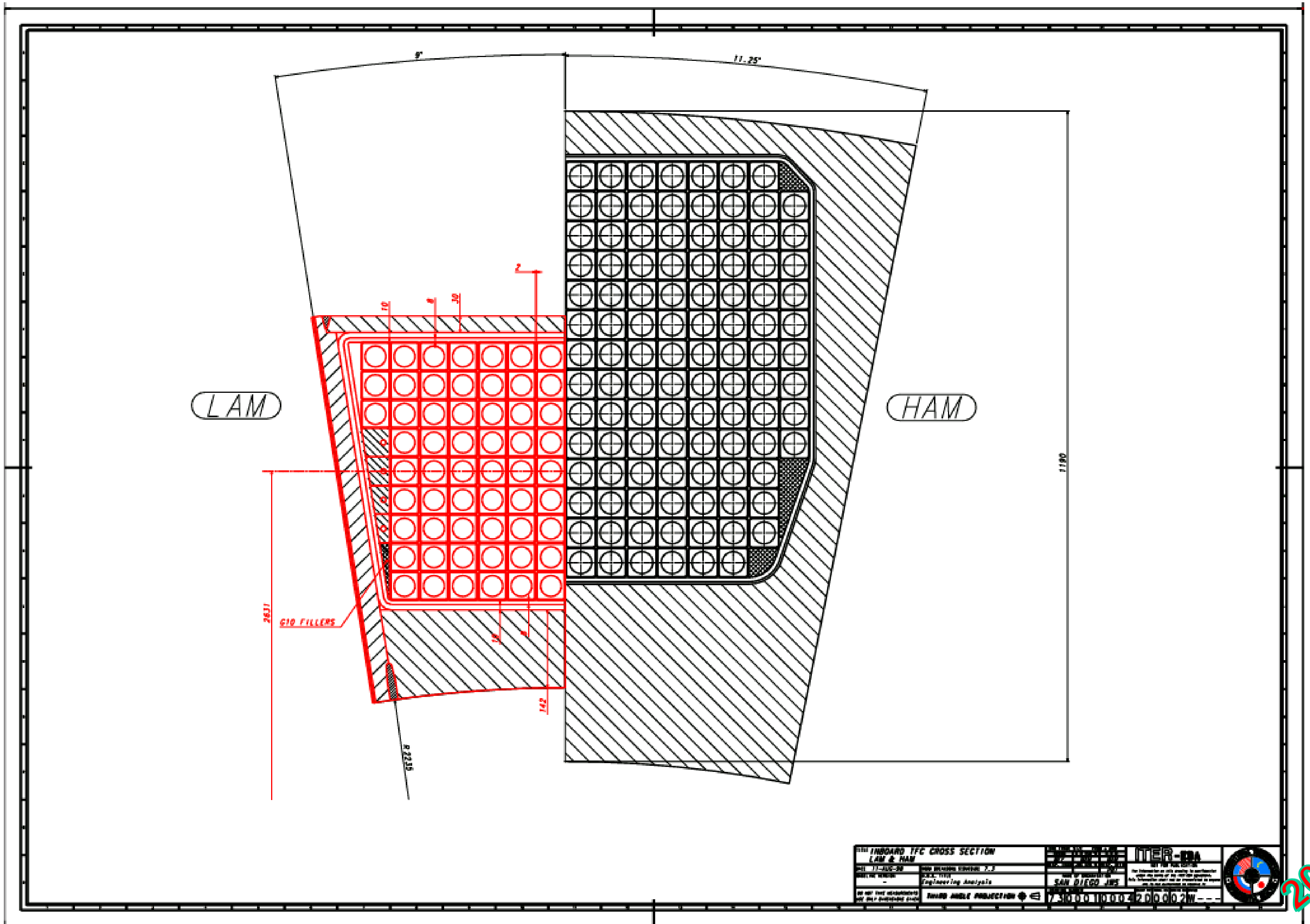
Machines with different R/a – TFMagnet section



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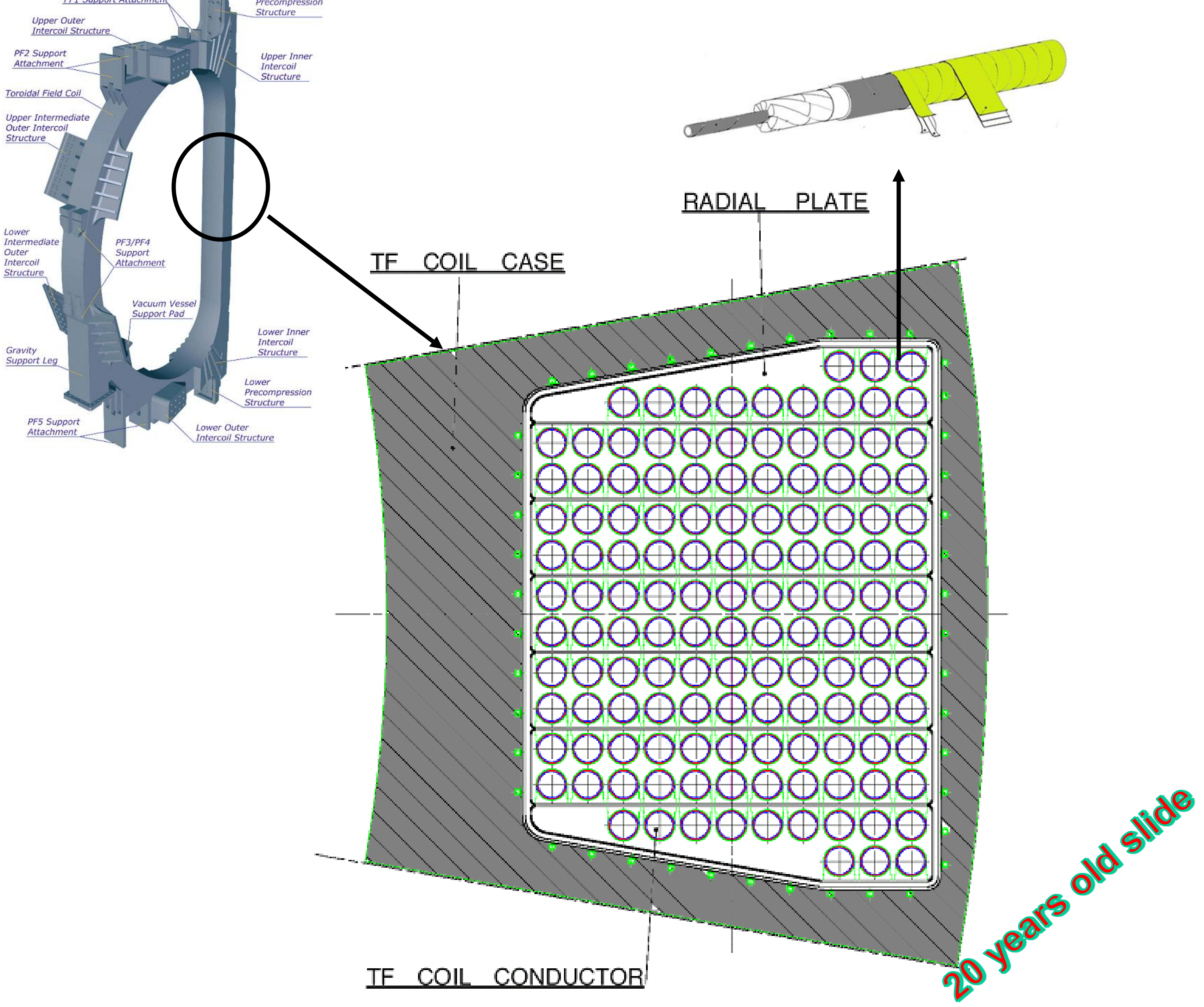
TF Cross section % usage by :	
Cable	**12.8%**
Non Cu (Nb3Sn)	4.0%
Cu	8.7%
Insulation	**14.2%**
Cable insulation	4.4%
Insulation between double pancakes	2.3%
Radial plate insulation	1.2%
Resin	4.2%
WP ground insulation	2.0%
Putty for cooling pipes	0.2%
Structural	**65.6%**
Cooling pipe jackets (in AP plate)	0.1%
Cooling pipes (in AP plate)	0.1%
Cooling pipes (in AU plate)	0.1%
Cover plates	6.9%
Radial plates	17.2%
Nickel plate	0.1%
Cable jackets and spiral	4.8%
Casing AU Plate	30.9%
Casing AP Plate	5.5%
Coolant	**7.3%**
He in cable (33 %) including spiral	7.1%
He in case cooling pipe	0.2%
Grand Total	**100.0%**



System Analysis: Design Drivers

- Radial Build: $\Delta \downarrow$ 10cm R $\downarrow$ 18cm C $\downarrow$ 60kIUA
  - Shielding (heating, damage, reweldability)
  - CS Magnet
  - TF Magnet
  - Assembly and tolerances
- Elongation: $\kappa_{95} \uparrow$ 0.1 R $\downarrow$ 17cm C $\downarrow$ 80kIUA
  - BUT …(Stability, VDE's, SN-DN control, Divertor space, flexibility)
- Triangularity: $\delta_{95} \uparrow$ 0.1 R $\downarrow$ 10cm C $\downarrow$ 100kIUA
  - BUT …(SN-DN control, Divertor space, Sawtooth R, Magnet loads)
- Safety Factor: $q_{95} \downarrow$ 0.1 R $\downarrow$ 5cm C $\downarrow$ 50kIUA
  - BUT …(HH degradation, Disruptions loads, Magnet loads)
- Confinement: H $\uparrow$ 0.1 R $\downarrow$ 12cm C $\downarrow$ 130kIUA

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