ITER status and application of integrated modelling to support design, operation and research plan

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Science Division, Science and Integration Department, ITER organization

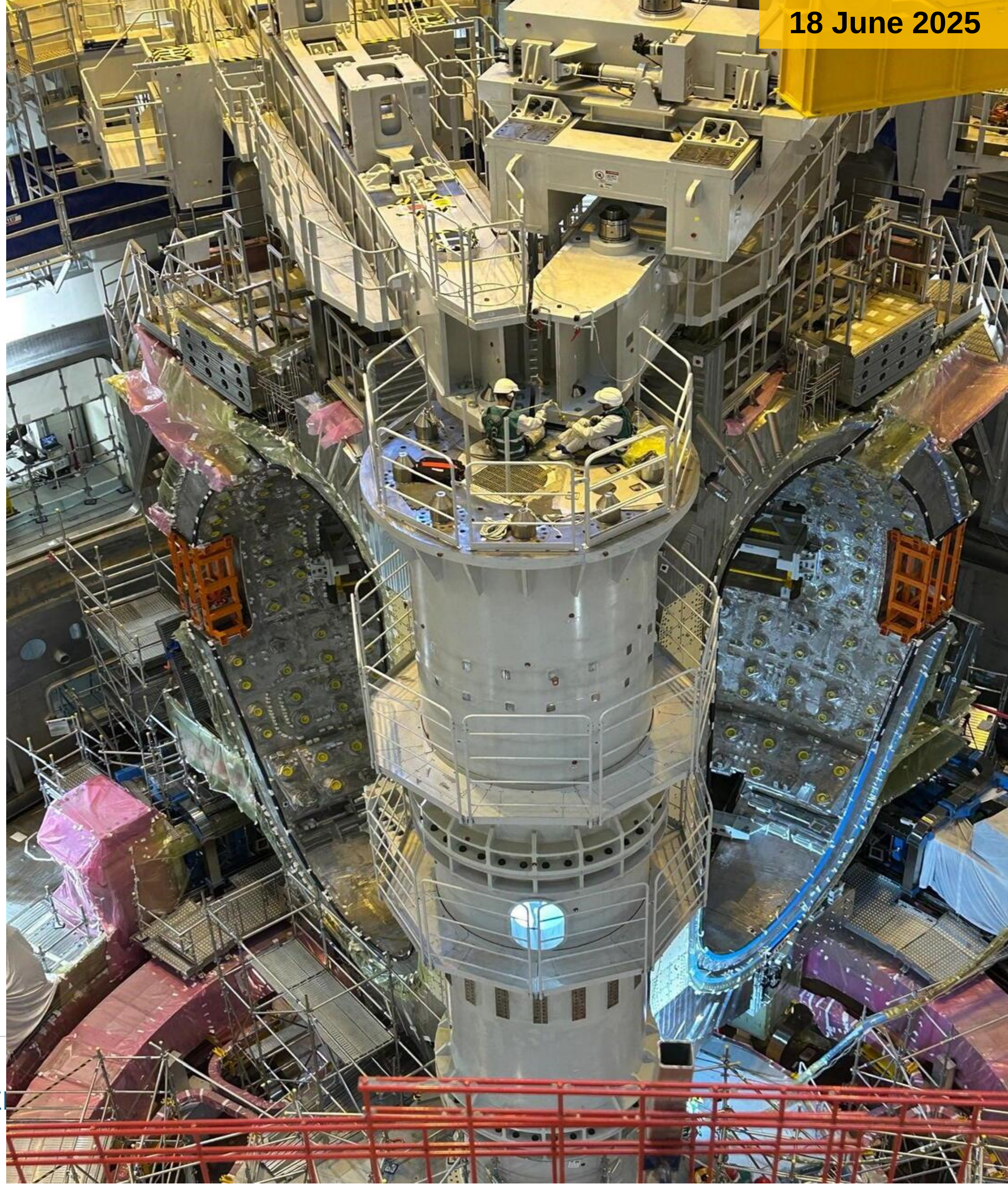
14th International ITER School, ITER Organization, 30 June 2025

china eu india japan korea russia usa

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

Outline

- Project status
  - Objectives and overall Design
  - Scientific Basis
  - Design: Key Components
  - History and organization
  - Construction Status
- New 2024 Baseline: key elements and rationale → use of integrated modelling
- Revised Research Plan and main elements → use of integrated modelling



Objective and Design

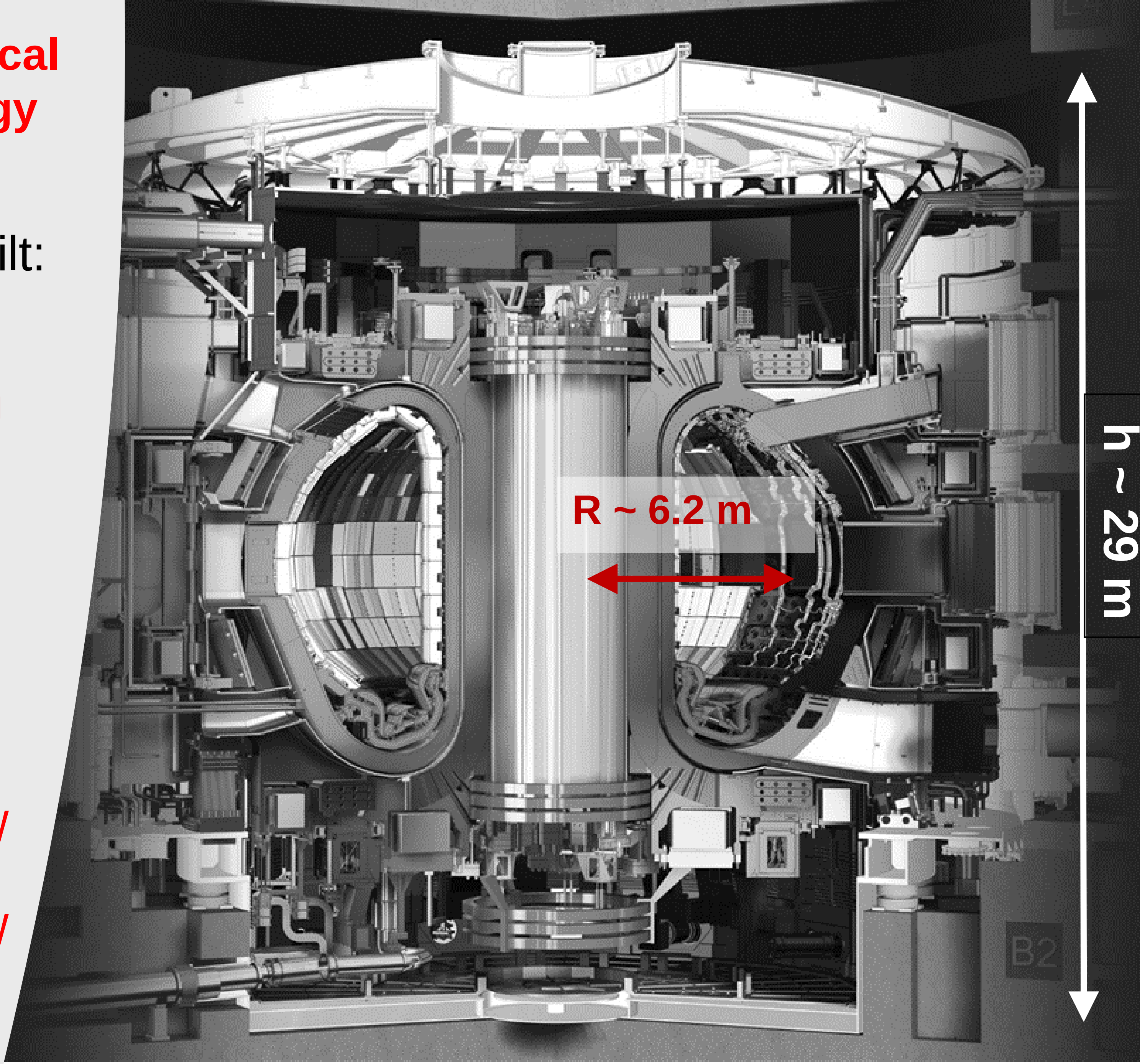
Demonstrate the scientific and technical viability of fusion energy as an energy source for humankind

ITER is the largest tokamak ever built:

- Major radius: 6.2 m
- $B_T \leq 5.3$ T, $I_p \leq 15$ MA
- Total stored magnetic energy: ~50 GJ
- Plasma volume: >800 m^3
- Vacuum Vessel volume: 1000 m^3
- Device weight: ~23,000 tonnes
- Cryostat: 29 m wide, 29 m high, 16,000 m^3

High gain fusion power scenarios:

- P_{fusion} = 500 MW with $P_{heat} \leq 50$ MW
  $Q \geq 10$ for 300 - 500s
- P_{fusion} ~ 400 MW with $P_{heat} \leq 80$ MW
  $Q \geq 5$ for 1000 - 3000s
  (steady-state)



Scientific Basis

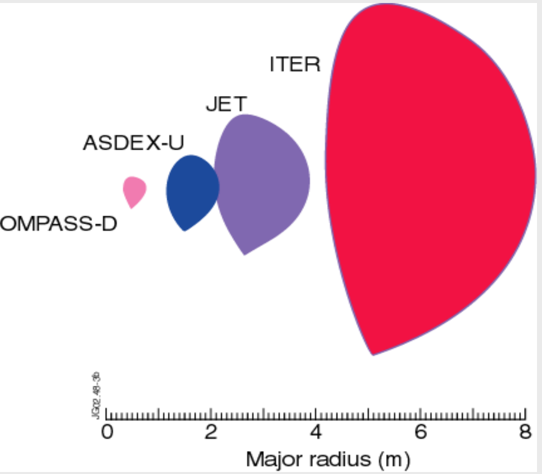
ITER design basis : Size and τ_E

- **Fusion energy production**

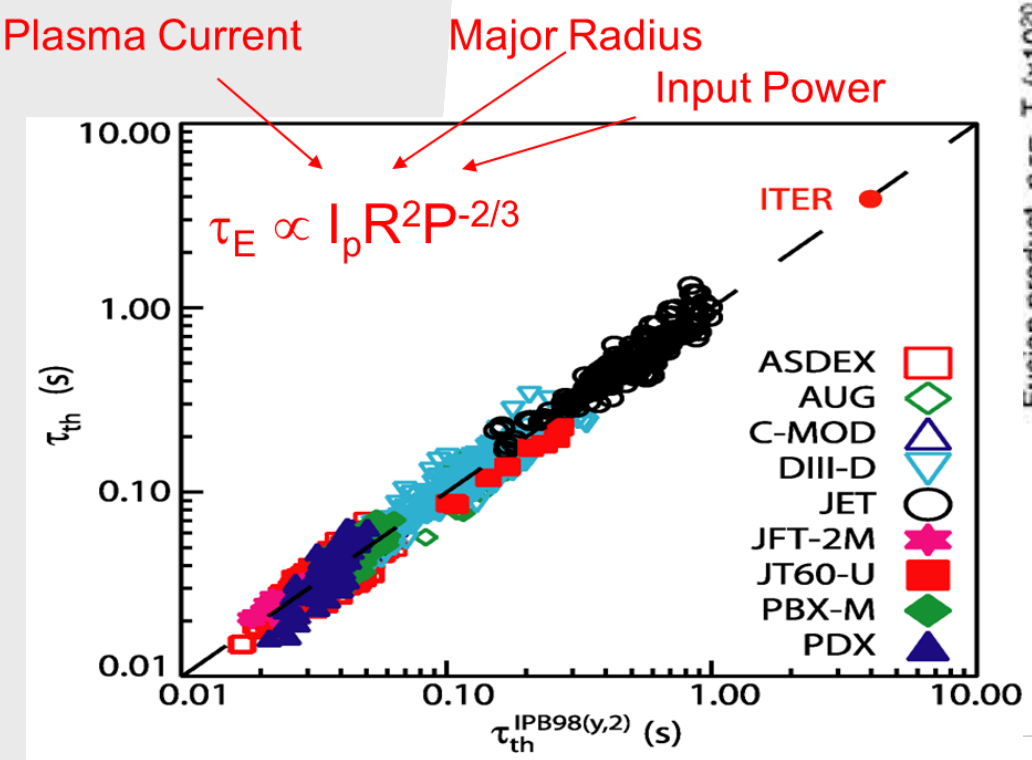
$Q = P_{fusion}\ (^4He + n)/P_{external\text{-}heat}$

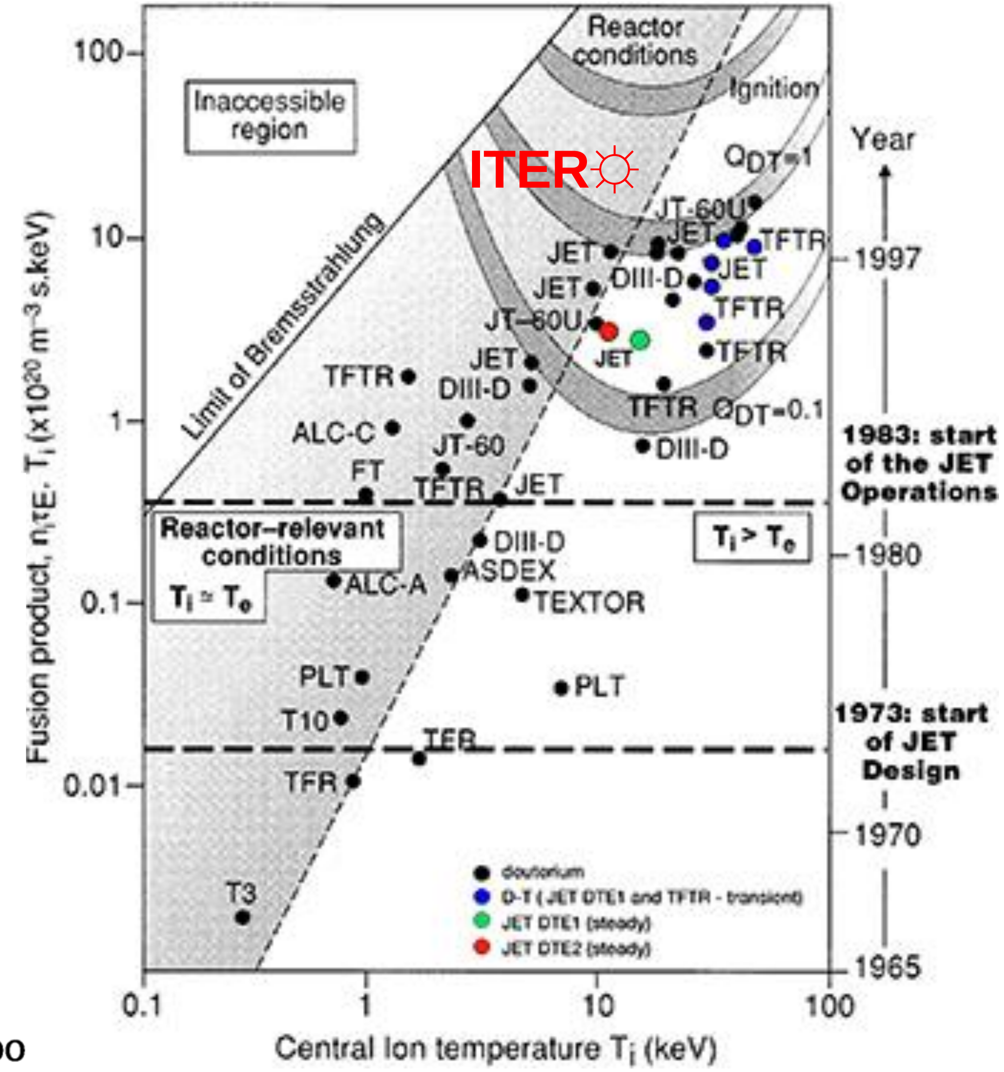
$Q = 10$ with $P_{fusion} = 500$ MW in ITER

$P_\alpha = 2\ P_{aux}$



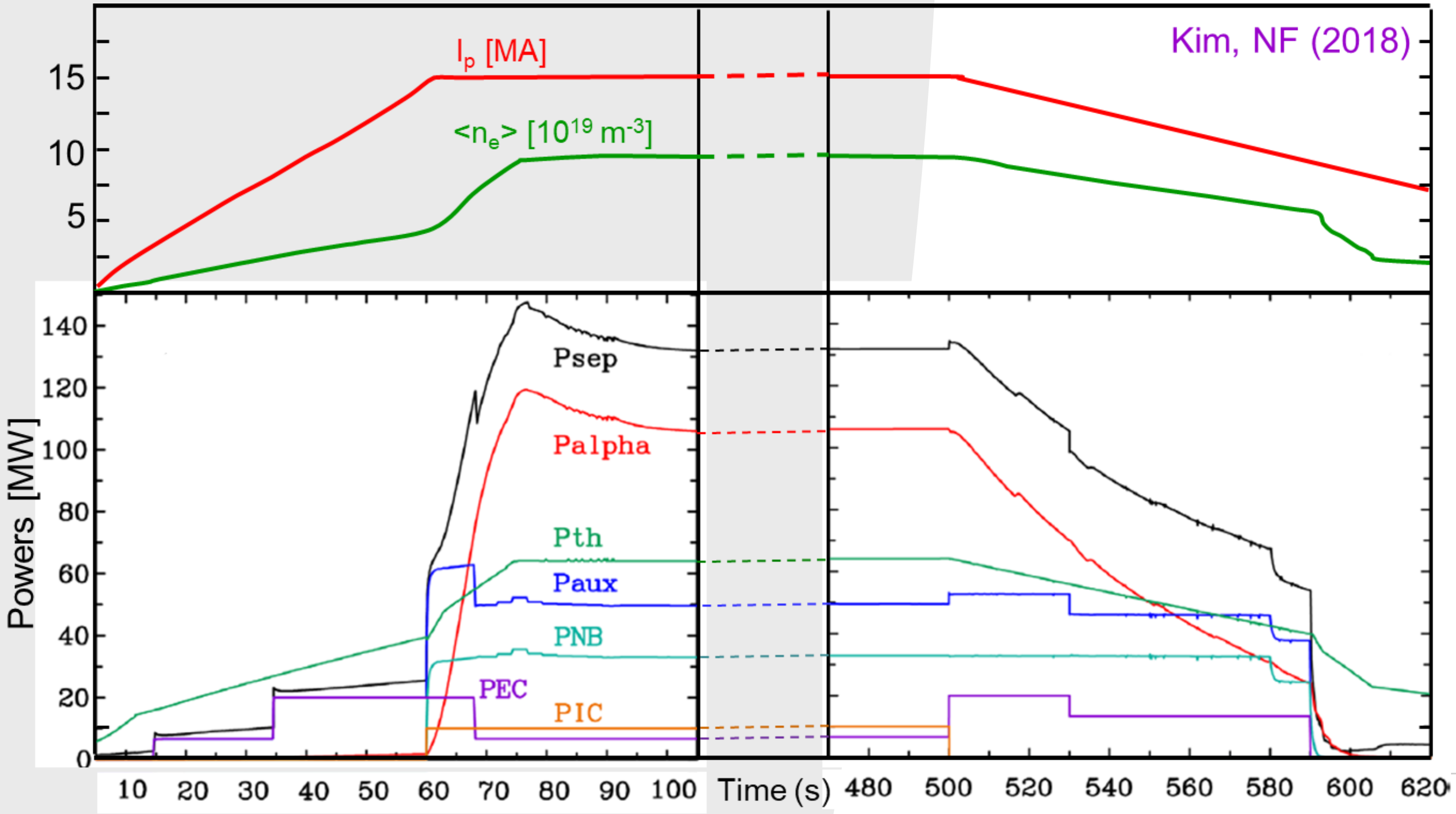
$q_{95} \sim aB_T/RB_p \geq 3$

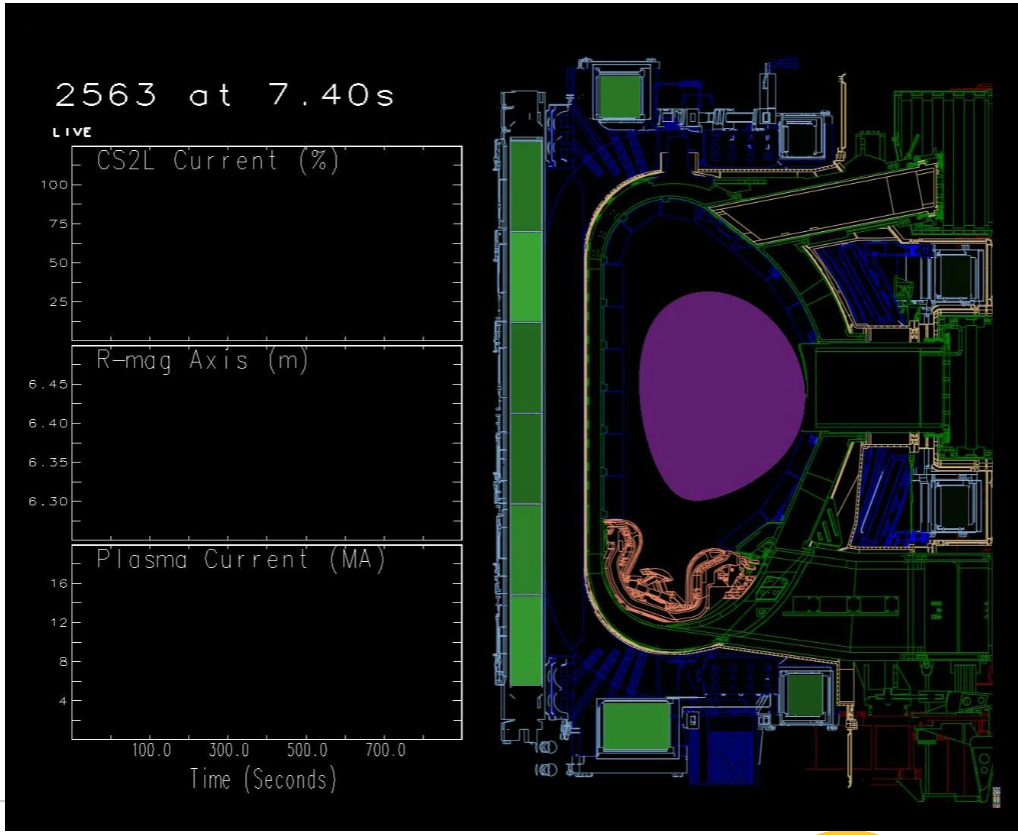




ITER Q = 10 scenario (300 – 500 s burn)

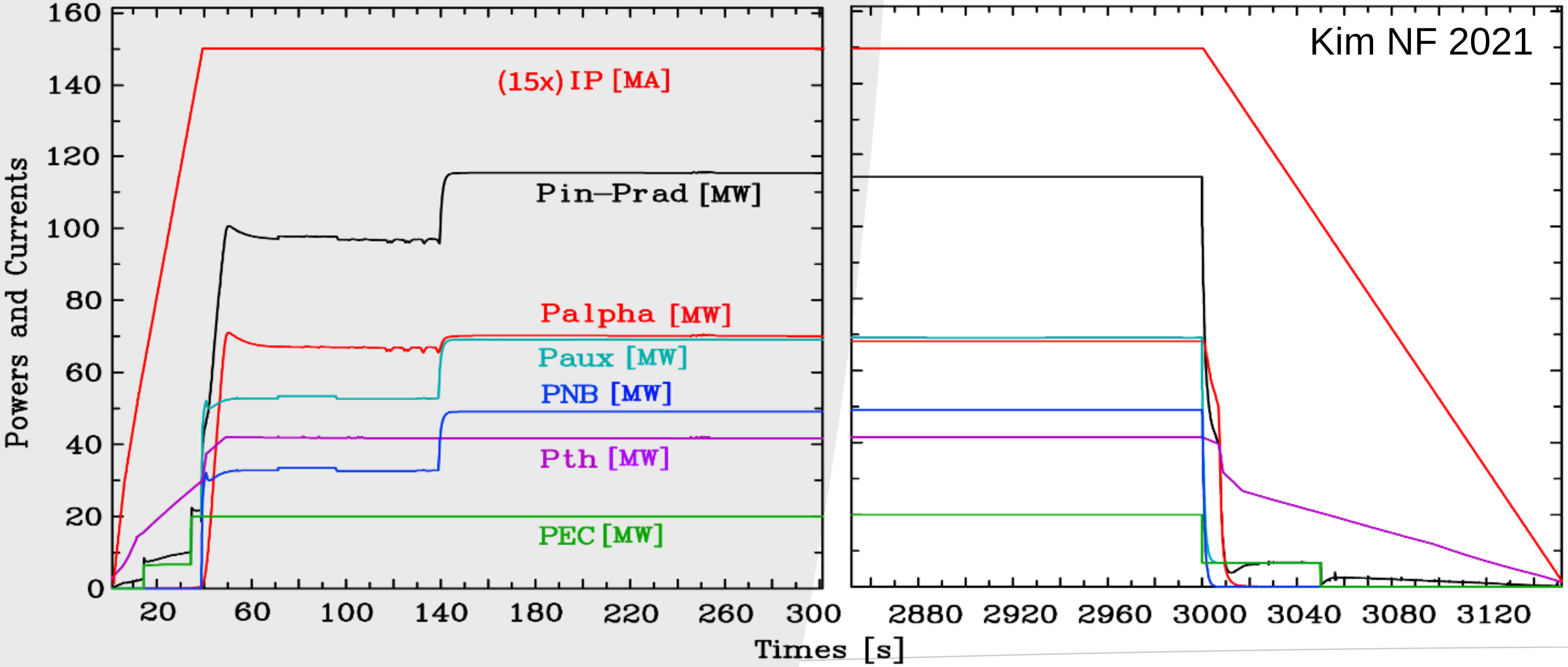
- Based on conventional sawtoothing H-mode with H_{98} = 1 → scenario used for the design of magnets and components (15 MA/5.3 T)
- $P_{aux} = P_{NBI} + P_{ECH}$ (+ P_{ICH}) ~ 50 MW → Alpha-heating dominant scenario with non-inductively driven current ~ 35%

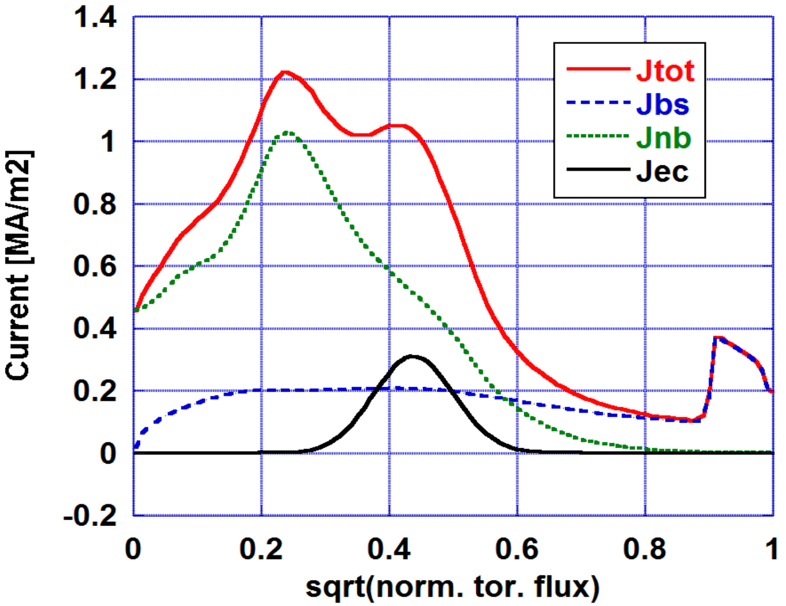




ITER Q ~ 5 scenario (steady-state)

- 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%

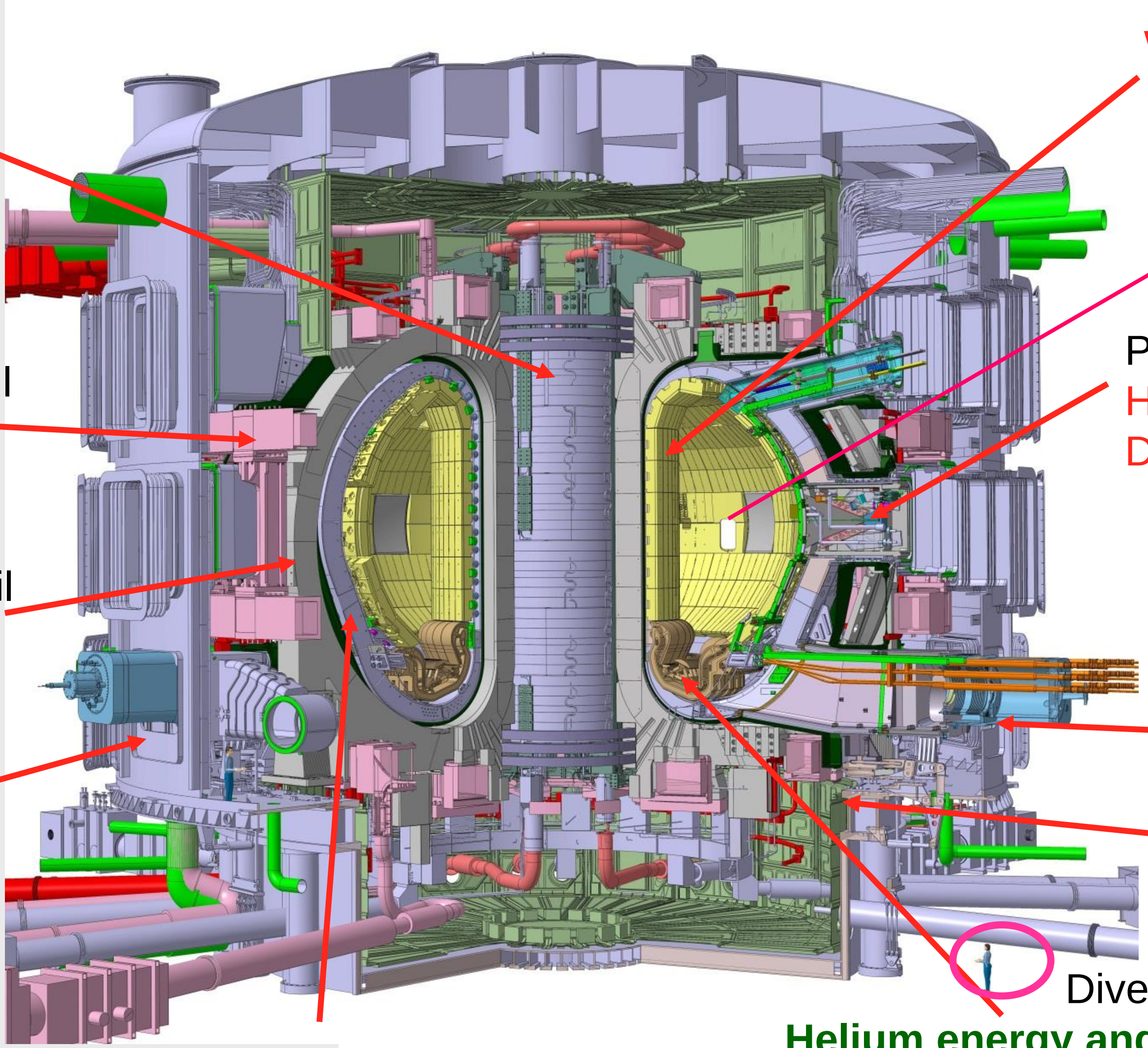




Polevoi NF 2020

Design : Key Components

Main ITER Components



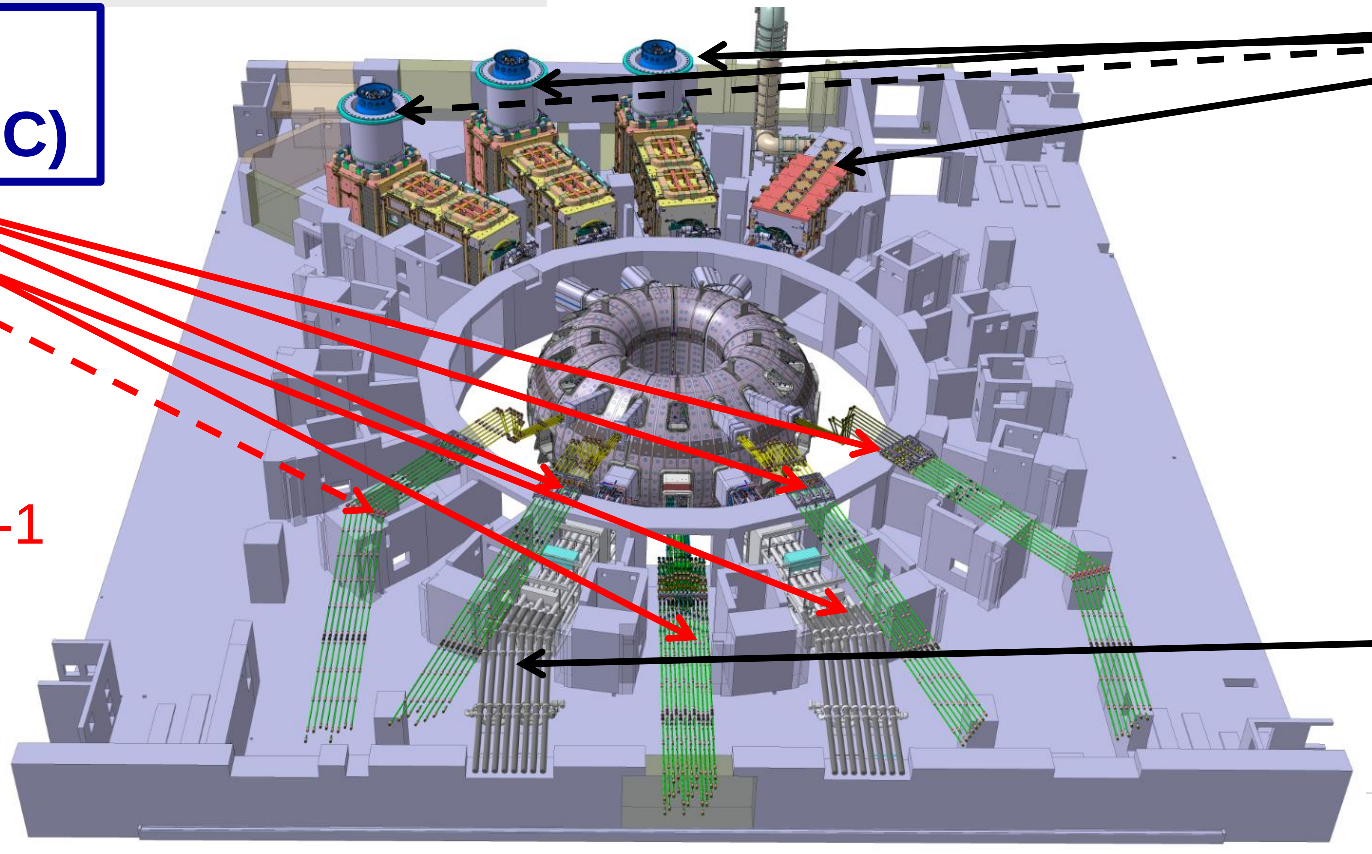
Heating and Current Drive

Large H&CD installed power and optimized power mix

High flexibility for experimental programme, reduction of risks to achieve Q = 10

Electron Cyclotron (EC)

170 GHz
40 MW - SRO
+
20 MW (+7) – DT-1



Neutral beam injection (NBI)

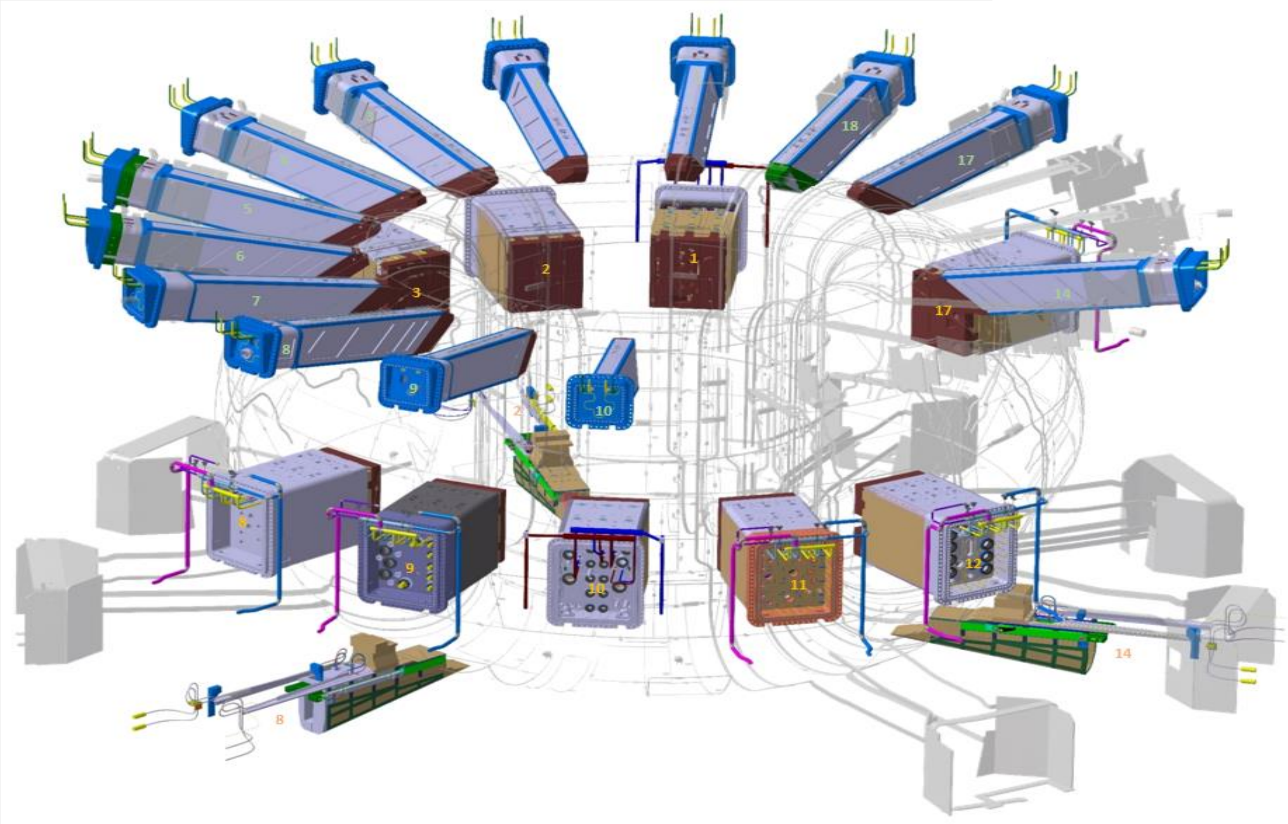
870 keV H^0
1 MeV D^0
33 MW (+16.5)

Ion Cyclotron (IC)

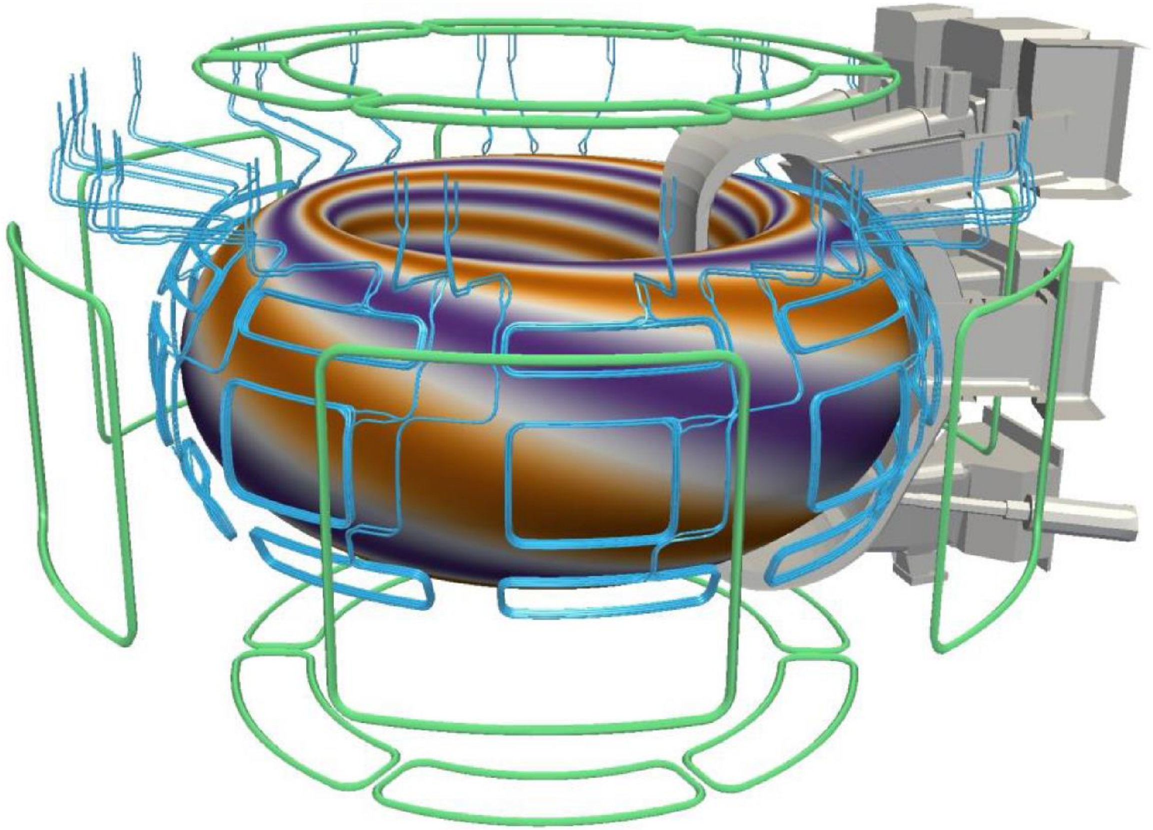
50 MHz
10 MW – SRO
10 MW (+10) – DT-1

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

- ❑ Diagnostics: ~ 60 instruments measuring ~ 100 parameters



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

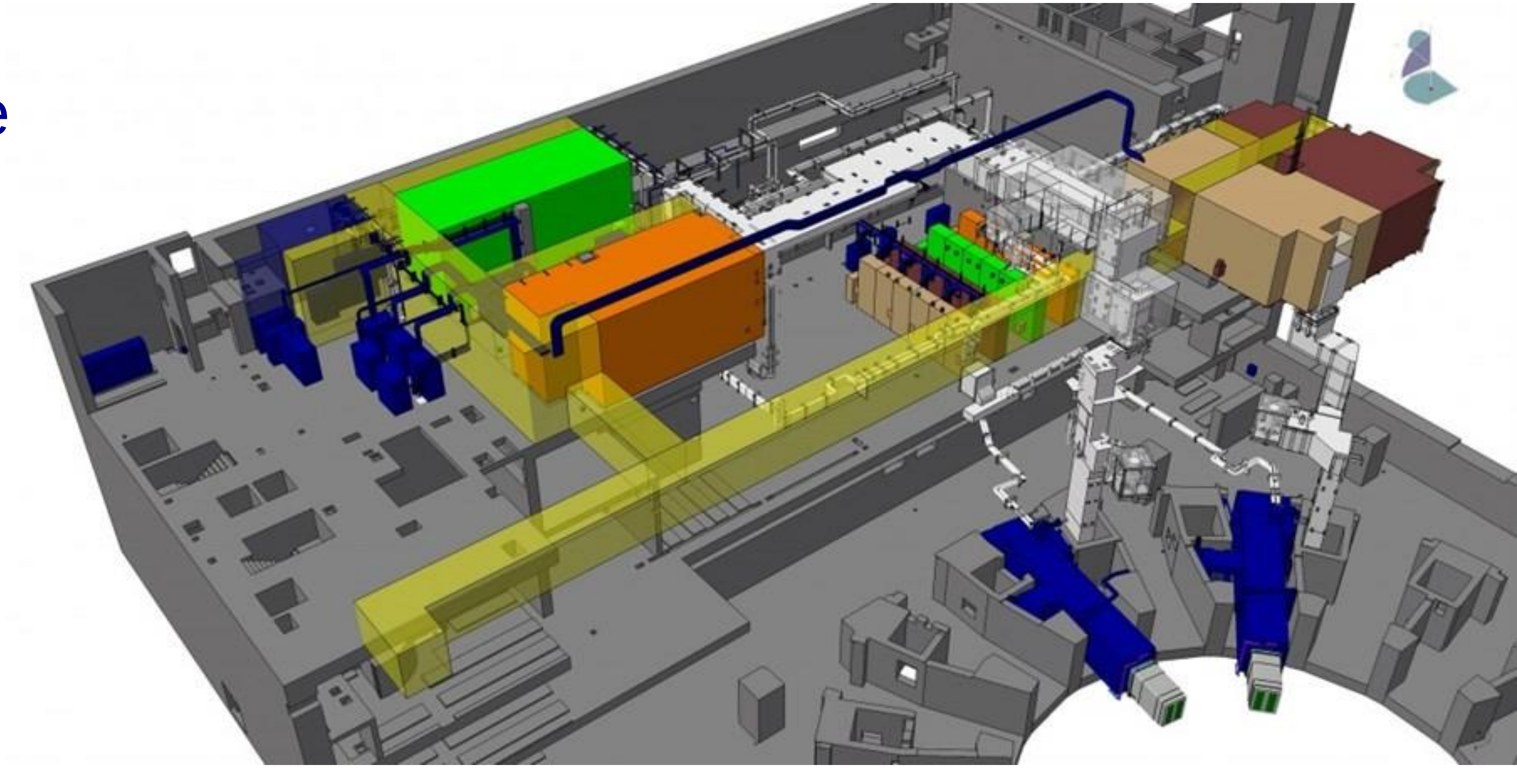


Tritium Breeding : Test Blanket Systems

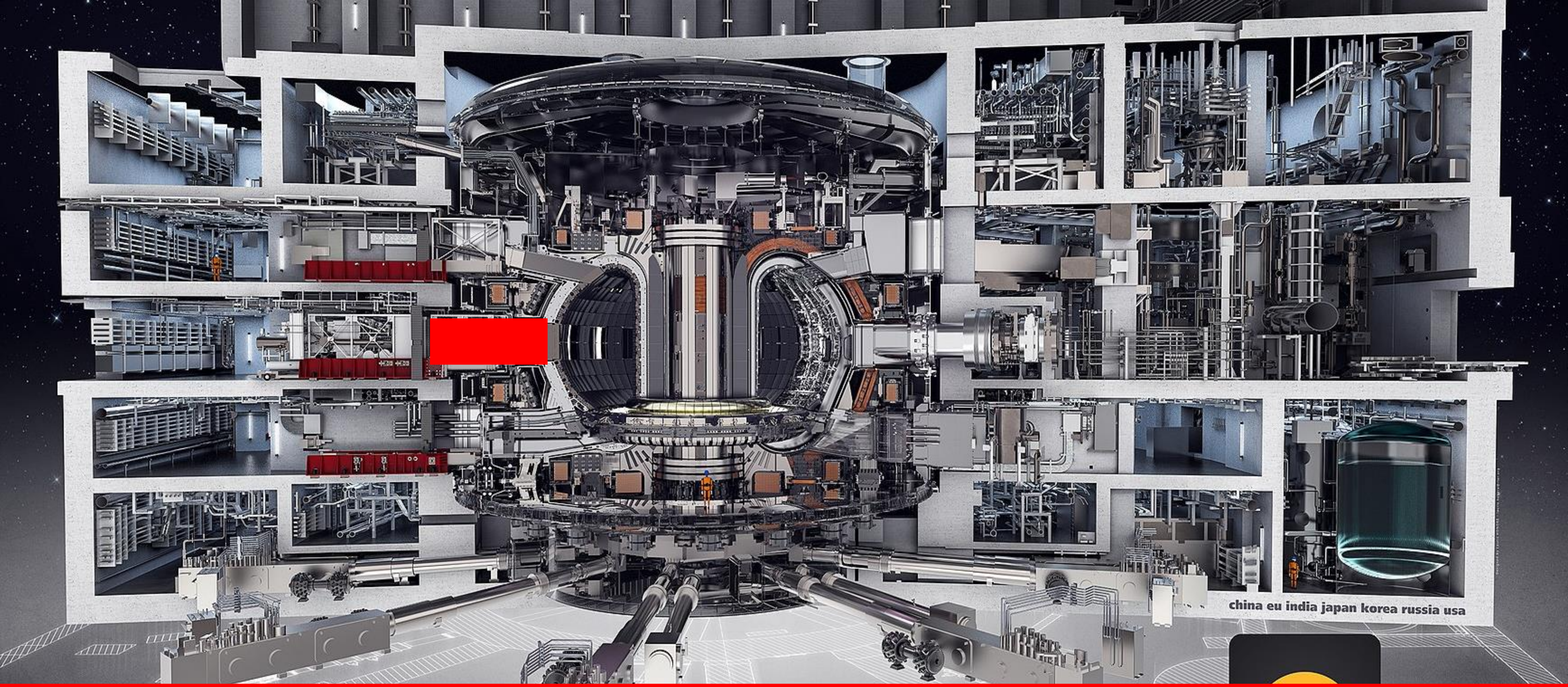
Tritium not available in sufficient amounts for large scale nuclear fusion energy production → Tritium needs to be produced in-situ (n + Li → T + He)
T production schemes will de demonstrated in ITER (at small scale)

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



Demonstration of the achievement of coolant thermo-hydraulics conditions (both water-coolant and Helium-coolant) relevant for high-efficiency electricity production

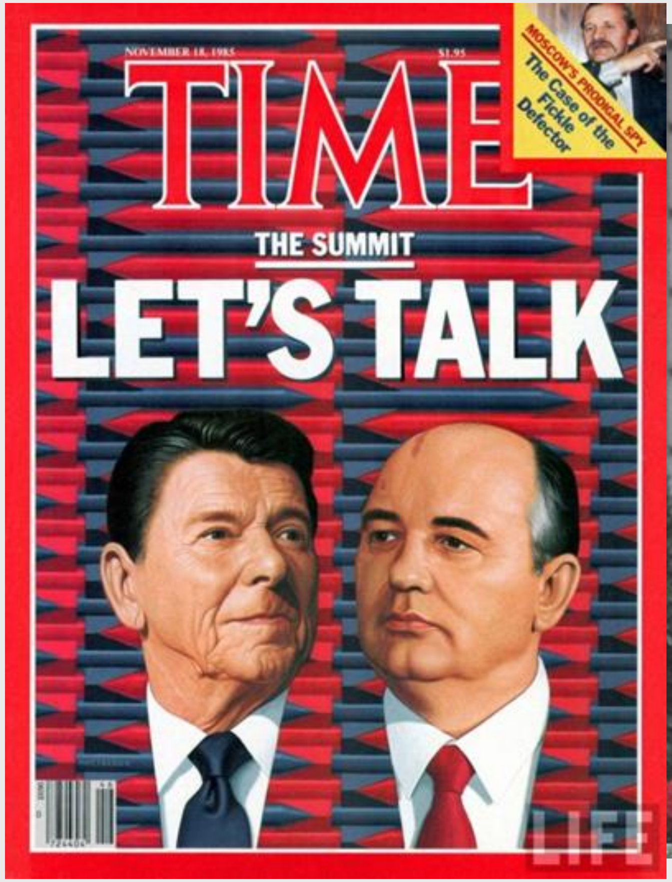


ITER will maintain self-heated DT plasmas by the fusion reaction for durations of 10 minutes to 1 hour. ITER will demonstrate in an integrated way the technology, materials and physics needed to produce electricity in commercial fusion reactors

History and Organization

ITER's History

The origin of the idea is the super-power meeting in Geneva on 1 November 1985: Gorbachev and Reagan signed an agreement to create an international project to develop fusion energy



"All the News That's Fit to Print"

The New York Times

Late Edition

VOL.CXXXV. . No. 46,601

Text of the Joint U.S.-Soviet S

Security

Nuclear and Space Talks

Chemical Weapons

Risk Reducti

Nuclear Nonp

Process of Dialogue

Civil Aviation Consulates

Environmental Protection

Fusion Research

The two leaders emphasized the potential importance of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentialy inexhaustible, for the benefit for all mankind.

ITER

Global Challenge, Global Answer

- 28 June 2005: The ITER Members unanimously agree to construct ITER at the site proposed by the European Union
- 21 November 2006: Signature of the ITER Treaty at the Élysée Palace in Paris

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

China EU India Japan Korea Russia USA

ITER Organization

The intergovernmental organization was formally established on 24 October 2007

Its objective is to promote cooperation among ITER Members:
China, EU, India, Japan, Korea, Russia and   USA

It is the project integrator and the nuclear operator of the ITER facility

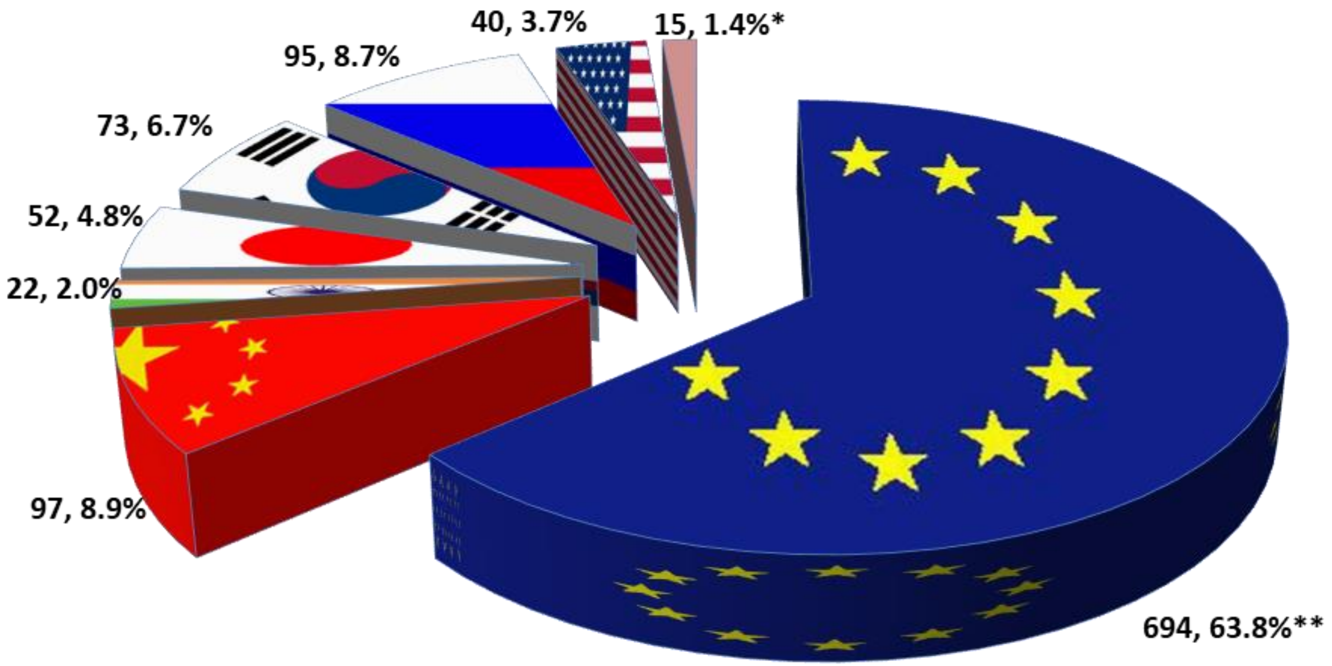
A collaboration for 35 years to develop fusion energy to the point that allows the design and construction of a demonstration fusion reactor

Contribution to ITER construction and ITER staff

A unique characteristic of ITER is that most of its components (~ 90 %) are provided in kind by the ITER Members

In-kind contribution proportions:

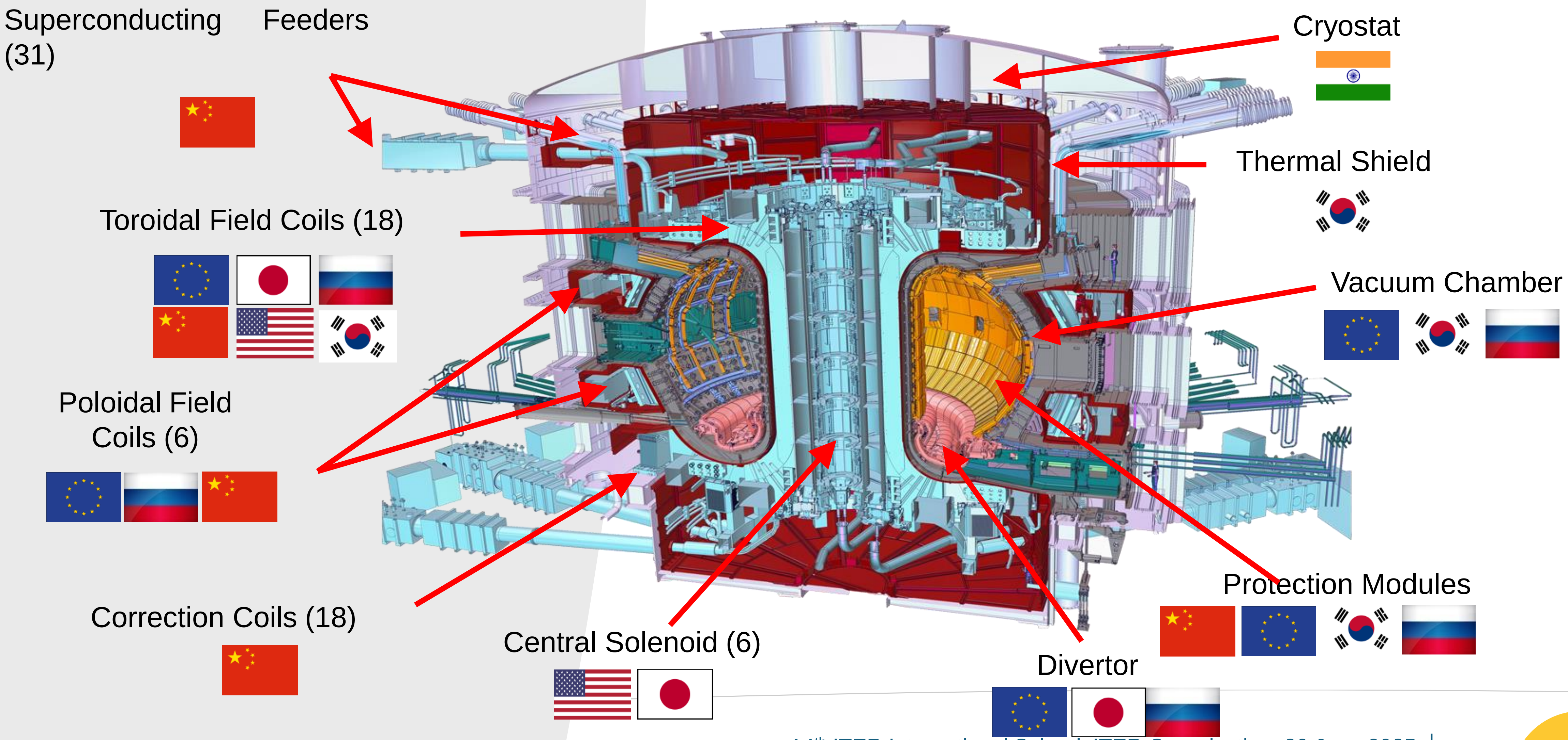
EU: 5/11
Other 6 Members: 1/11 each



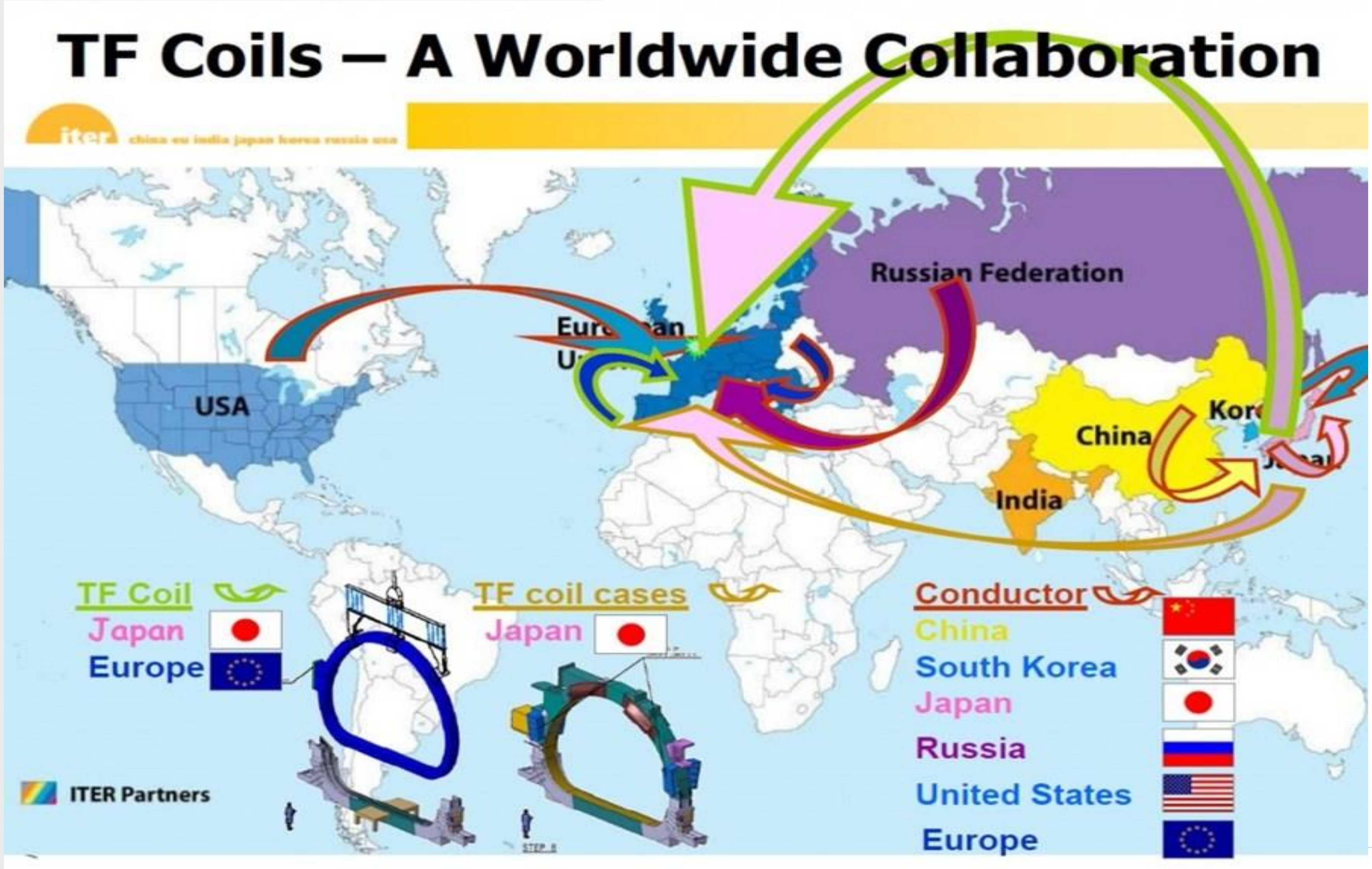
IO Staff by Member (G, P & Higher)
(incl. TCWS, VAS, PostDoc & SCSN)
**1.4% Others refers to to Uk, Switzerland, Ukraine*
*** Since Brexit: 22 Uk staff acquired EU nationality (19 French, 2 Irish, 1 Germany)*

Who makes what?

All intellectual property is shared among the seven Members



ITER Toroidal Field Coil Construction



Construction: before it all started

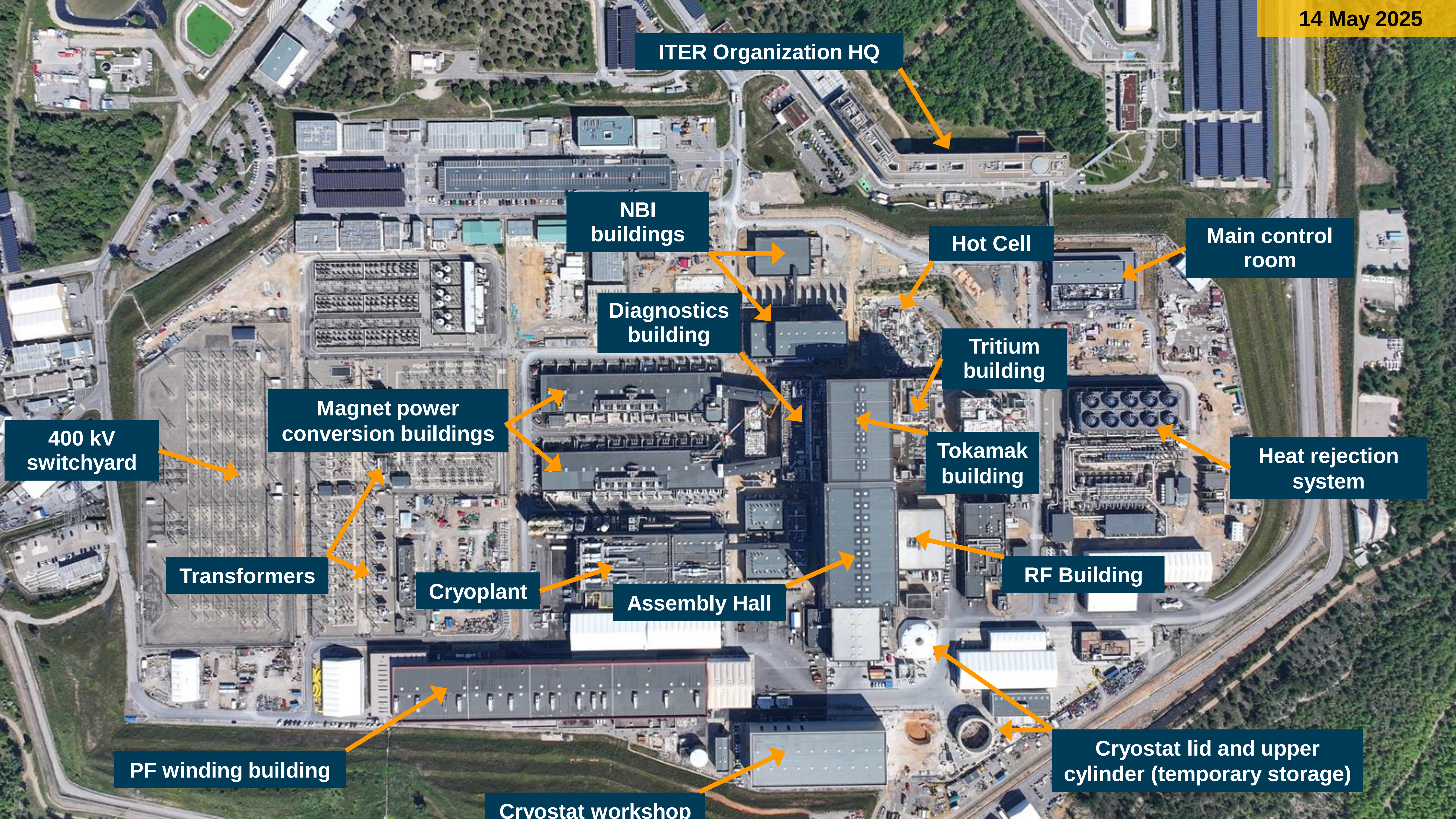
21 Jan. 2007

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

14 May 2025

Construction Site today (southwest view)

Construction Status


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

Cryogenic plant

Largest single unit plant in the world →

cools superconducting coils

(10.000 tons)

down to -269 ^{o}C

iter

ITER Control Room

Declared “ready for ITER Organization” in 2022

12 June 2022

19 Dec. 2022

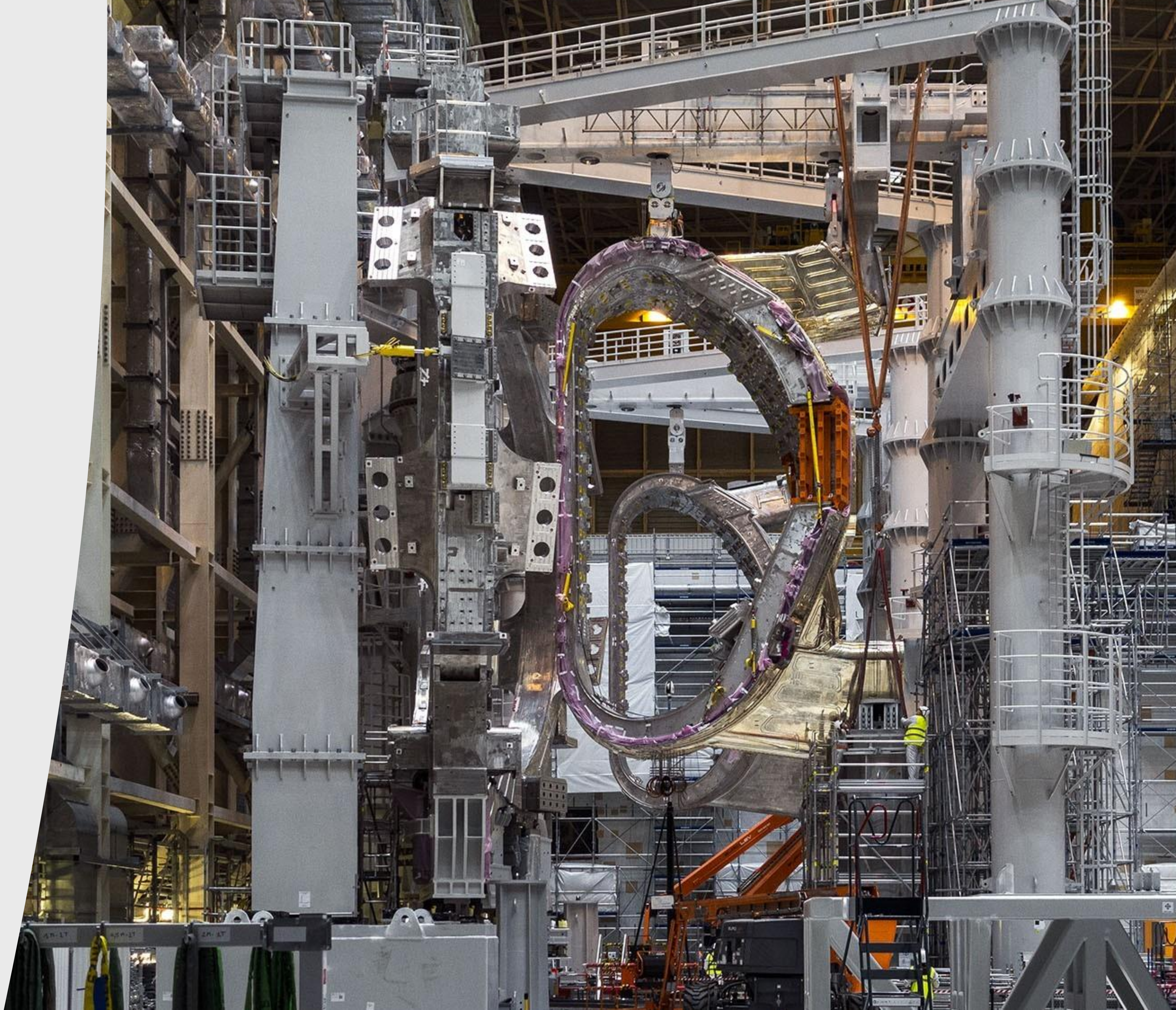
Symbolic first ever CODAC command issued from the Control Building

Progress on some main components

Vacuum Vessel

- 9 sectors (KO: 4, EU: 5) each 440 tonnes
- KO: all 4 sectors (6,7,8,1) at ITER site
- EU: Sector 4 (May 2025), Sector 5 (Sept. 2024) complete and at ITER site (built at Westinghouse-Mangiarotti)

- BUT repairs required/underway on all sectors … see later



8 Nov. 2024

9 May 2025

12 May 2025

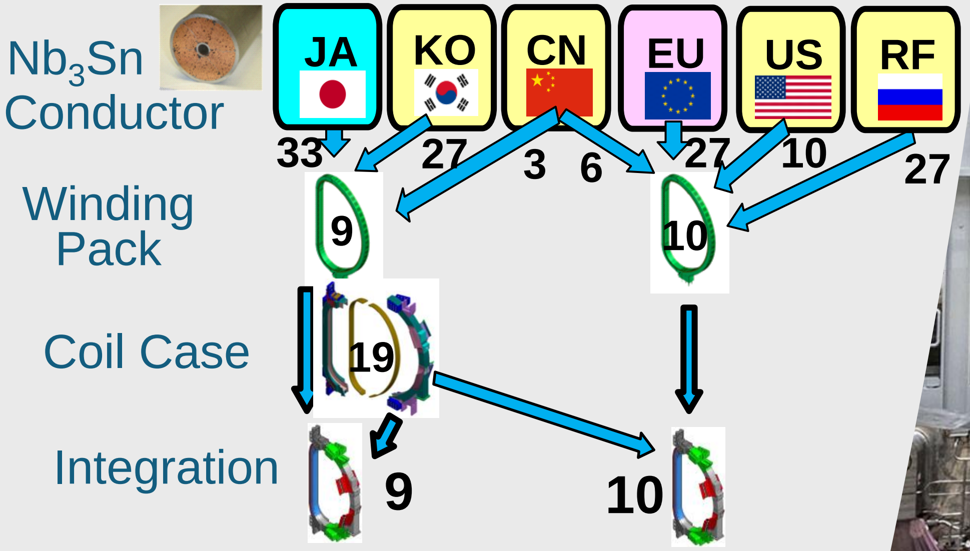
EU VV Sector 4 wrapped and in storage

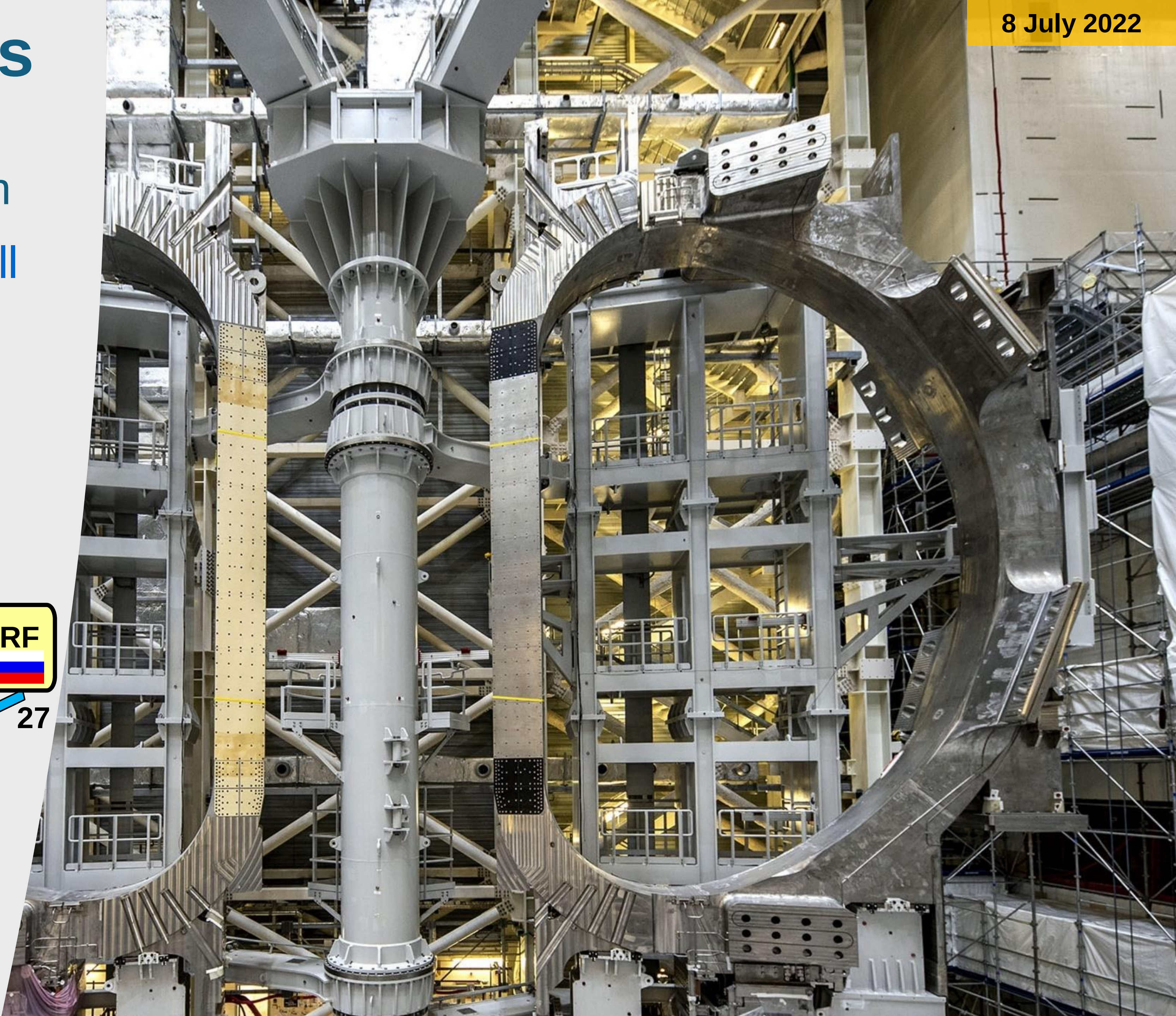
EU VV Sector 5 unpacked and placed on transport frame in the Cryostat Building

Toroidal Field coils

8 July 2022

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

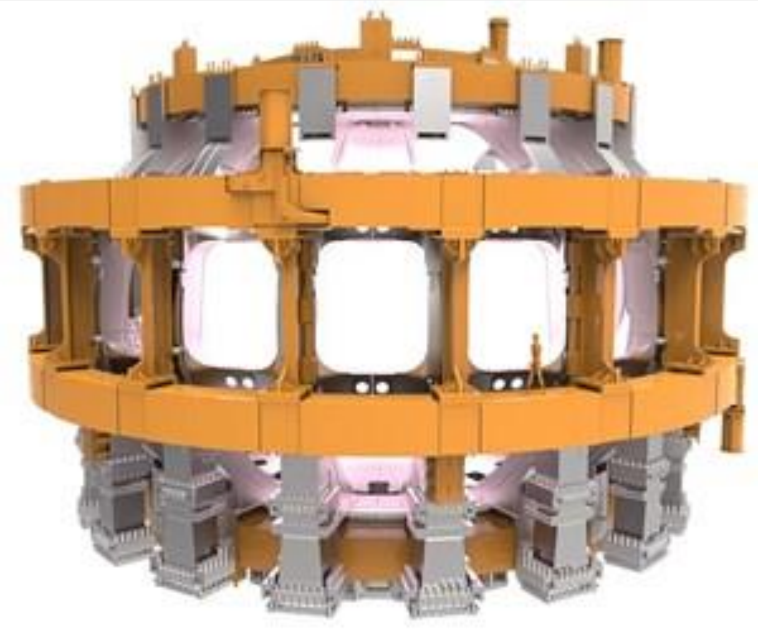




15 Apr. 2024

Poloidal Field coils

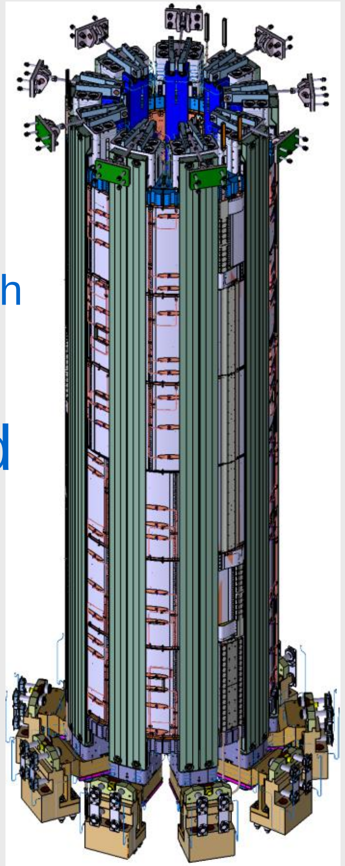
- NbTi, 6 T, 45 kA,
  Largest coils (PF,3,4), 24 m diameter, 400 t
- Manufacture complete → all PF1 (RF), PF2,3,4 (EU) in storage, PF5 (EU) and PF6 (CN) in-pit



PF3: being moved into storage

Central Solenoid

- Nb_3Sn, 13.5 T, 46 kA, 6 modules, ~4 m wide, total stack height ~20 m, > 1000 t
- Manufacture ongoing → 3rd module stacked in April 2024, 4th module delivered end 2023 and stacked in Dec. 2024
- Last two being delivered in



13 Jan. 2025

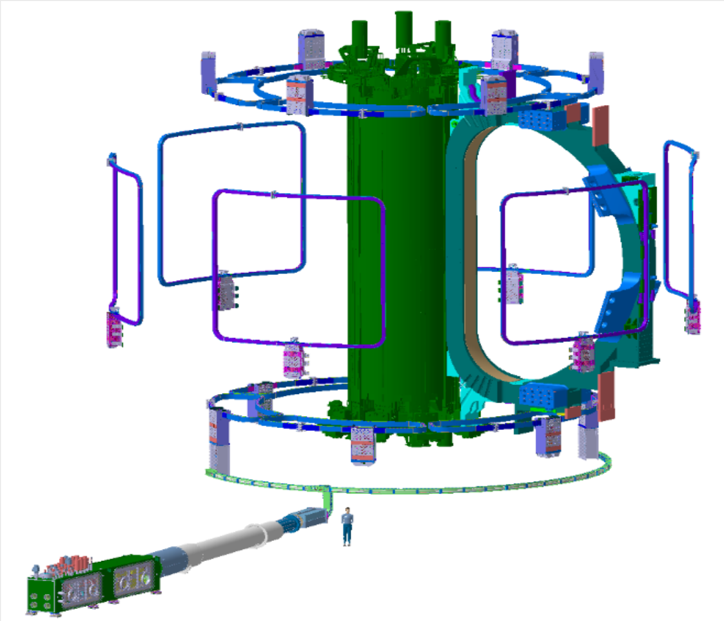
4 modules now in the stack

22 May 2025

5th CS module on transport ship in the port of Houston, Texas

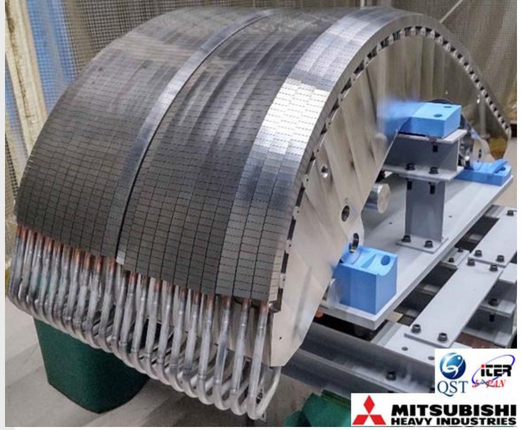
Error Field Correction coils

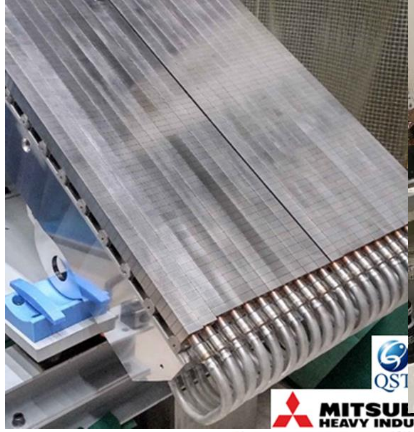
- NbTi, max: ±10 kA, 6x6 coils, largest 8.4 x 7.2 m, total weight 78 t
- All 6 top and bottom coils delivered, delivery of 6 side coils expected in 2025

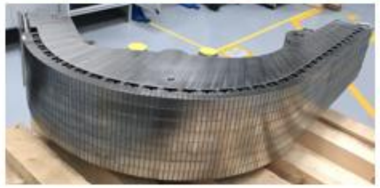


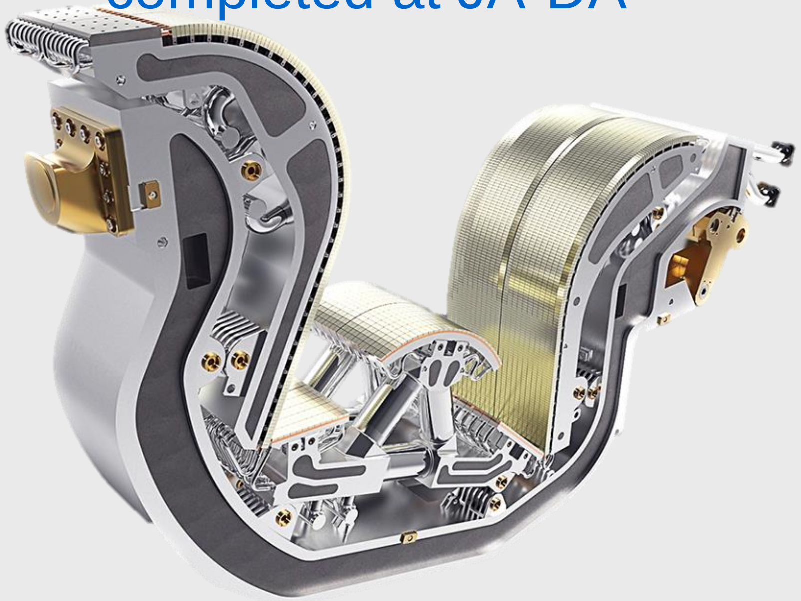
Divertor

- 54 Cassette Assemblies, 8 t each, ~140 m^2 W monoblocks and flat tiles
- Full-scale prototypes complete for all major components (IVT, OVT, Dome, CB) → supply chains established for manufacture in all concerned DA's → 3 OVT already completed at JA-DA









17 Dec. 2024

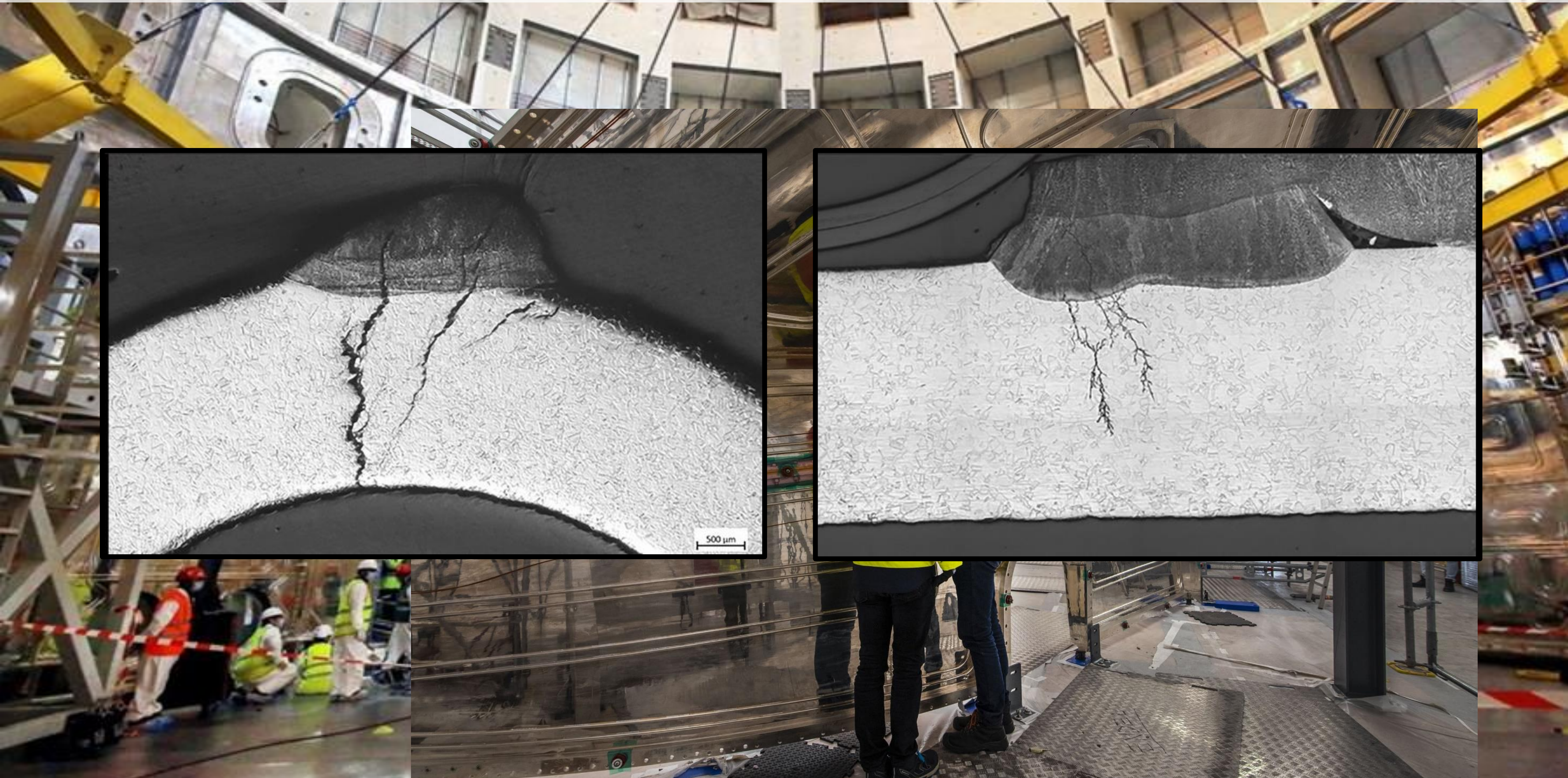
First batch of 48 Shield Blocks leave Donfang Electric Heavy Machinery Co., Ltd. in Guangzhou.
Now in Port-Saint-Louis-du-Rhône, awaiting transfer to IO for site acceptance tests later in 2025

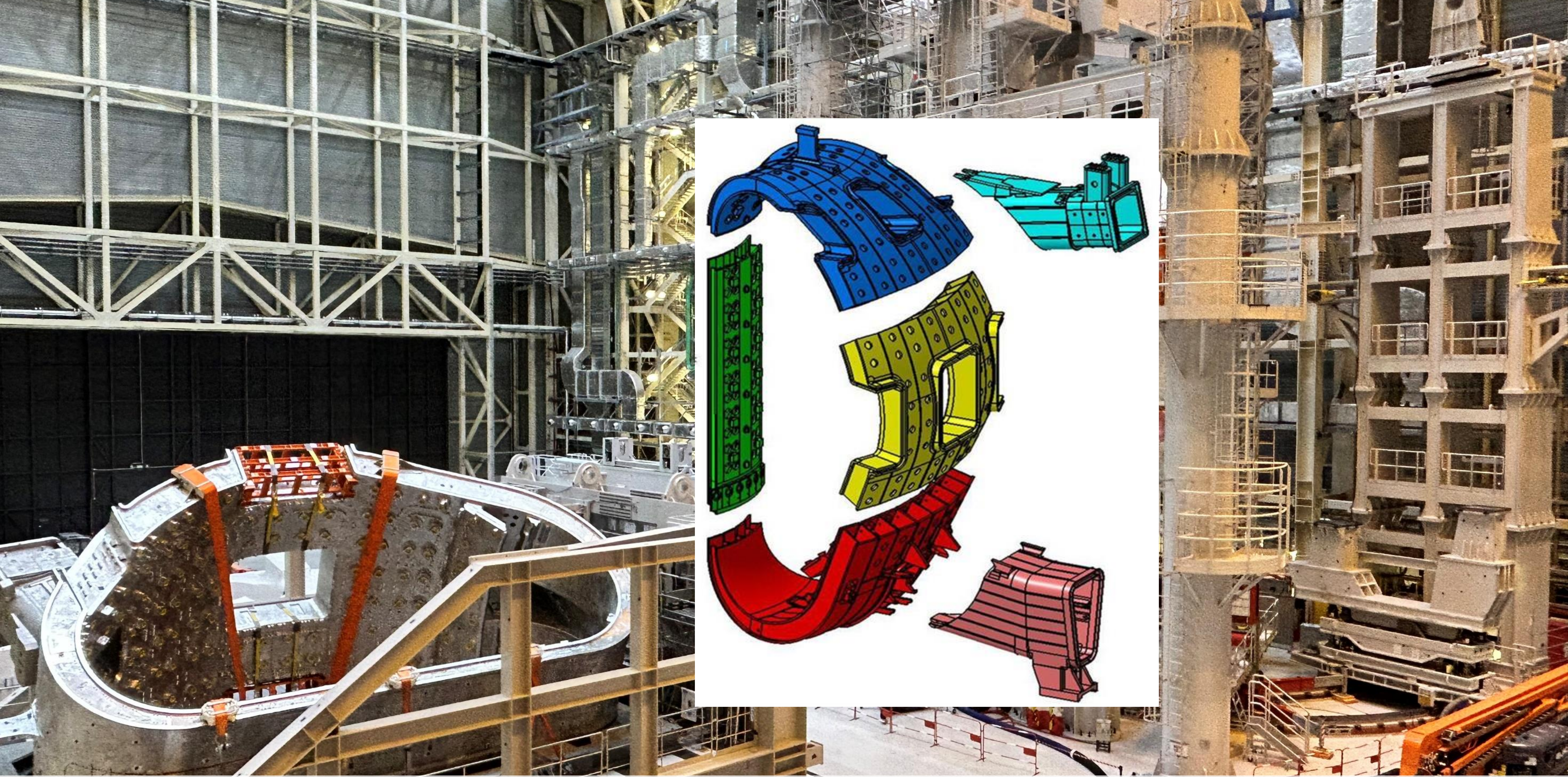
Issues with VV sectors and thermal shields

- Dimensional non-conformities in VV field joint contours on the 3 KO sectors delivered to IO turned out to be too large to permit sector-sector welding according to required standards
- Chloride stress corrosion cracking (SCC) found on many of the thermal shield (VV and cryostat) cooling pipes
- Major issues preventing continued assembly of VV sectors
- Issues have been discussed publicly, and details can be found here

https://www.iter.org/newsline/-/3818
and
https://www.iter.org/newsline/-/3830

SCC on thermal shields: problem found on several VV shields not yet installed on VV sectors → assumed to be present in many locations in VV and cryostat shields

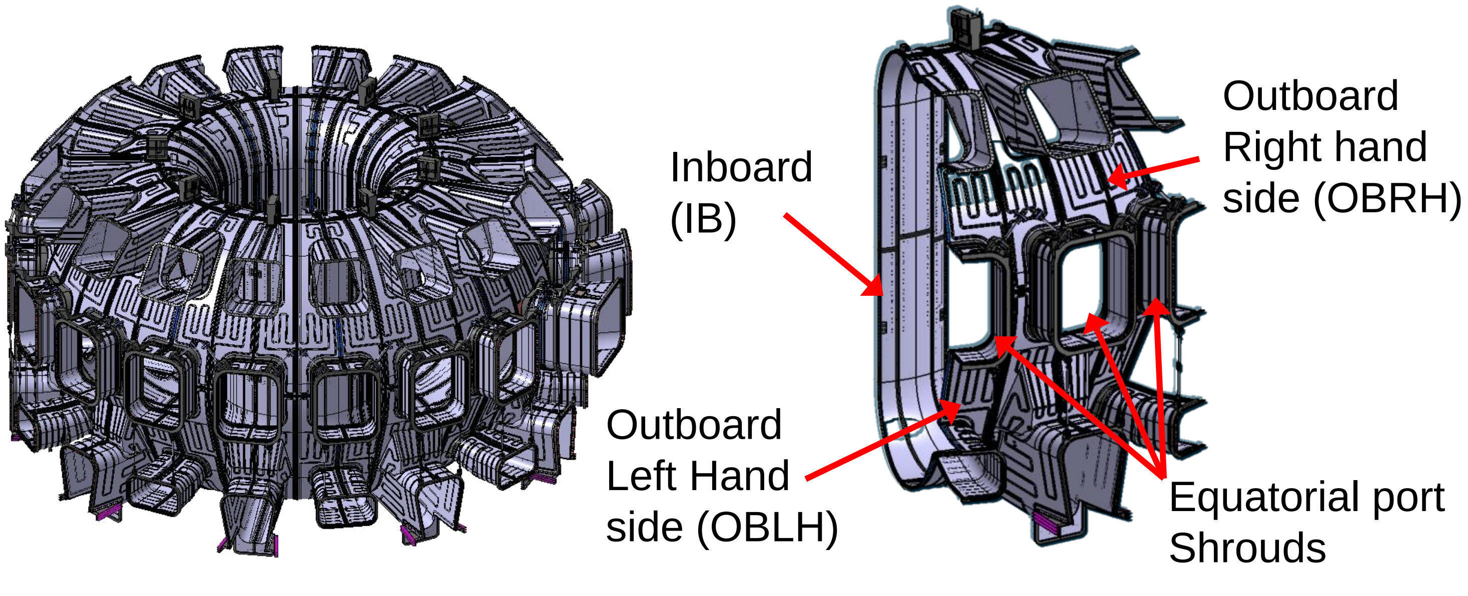




Some areas of non-conformity on VV field joints, particularly where the individual VV segments are joined

VV Thermal Shield repair + replacement

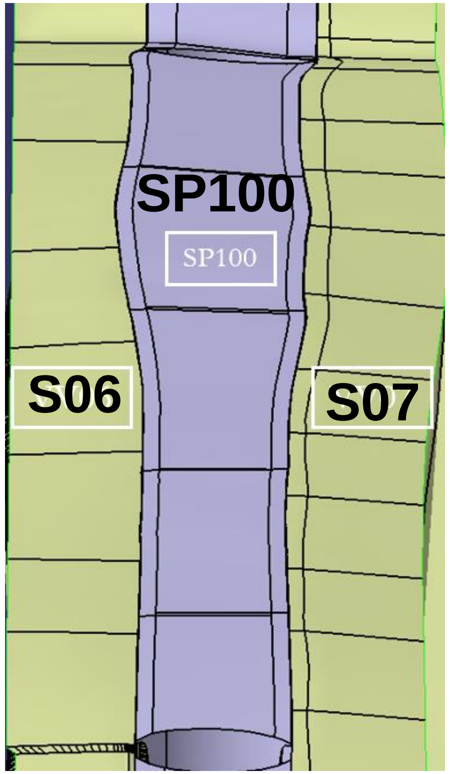
- Repairing 7 VVTS sets (21 panels)
- Remanufacturing 2 VVTS sets (6 panels)
  - Replace corroded pipes
  - 2 mm panel machining to eliminate potential panel corrosion risk
  - Surface polishing to replace silver coating → roughness ~80 μm → low emissivity at 80 K
- Progressing well → all to be completed in 2025

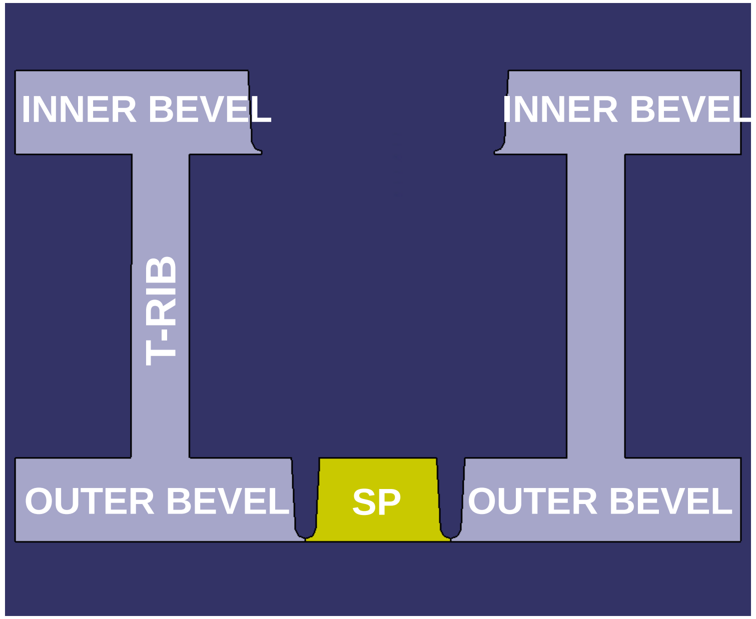


2nd CCTS OBRH pre-assembly test (INOX, India)

VV bevel joint repairs

- Vacuum build-up (manual / mechanized TIG)+ NDE (M-UT and RT)
  - Sectors 4,5,9,6,7: manual TIG; Sectors 1,8: mechanized and manual
- Bevel machining
  - Portable milling machine bolted to sector T-rib
- Sectors 6, 7 repaired in vertical position (SSAT)
- Sectors 1, 4, 8 in horizontal position (Cryostat Building)





12 Dec. 2024

VV status

- Sector 7 and 6: repair complete (SSAT), re-assembly complete and in-pit
- Sector 5 (on-site 25/10): repaired at supplier
- Sector 8 repairs in progress → forecast 31/07/2025
- Sector 1 repair underway, Sector 4 to start
- Sectors 2,3,9: manufacturing in progress (at EU supplier)

Repairs on Sectors 1, 8 in the Cryostat Worksh

18 June 2025

Sector Modules 6 & 7 in-pit

New 2024 Baseline: key elements and rationale

New Baseline rationale

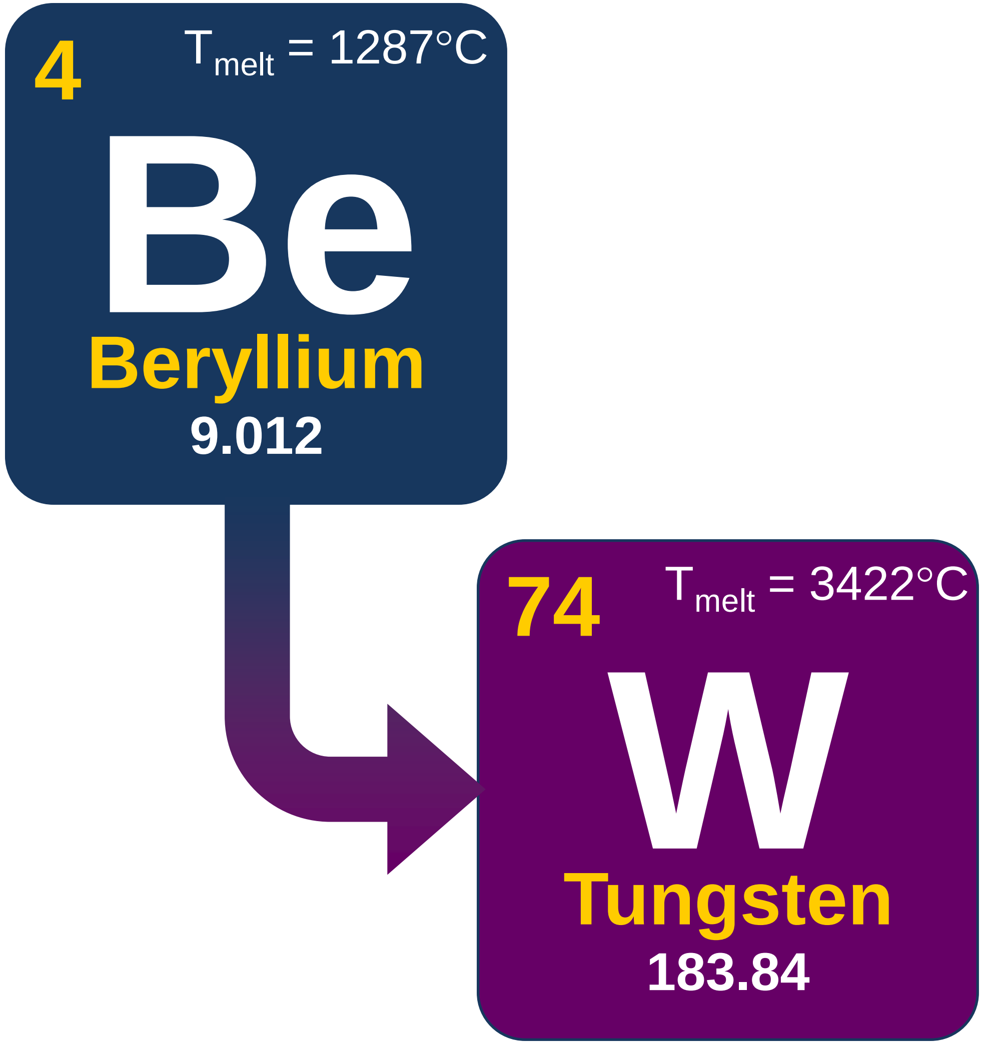
- Robust achievement of ITER Project goals, in view of past challenges (delays due to the Covid-19 pandemic, technical challenges in completing first-of-a-kind components and in nuclear licensing)
- Realistic and reliable assembly – commissioning - operation
- Achievement of earliest start of the ITER Nuclear Phase (DD operation) and minimization of technical risks → a new 1st phase **"Start of Research Operation" (SRO)**
- Stepwise safety demonstration (see next slide) → **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 heating mix + boronization → ease path to Q = 10 with added W

Why change to a tungsten First Wall?

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

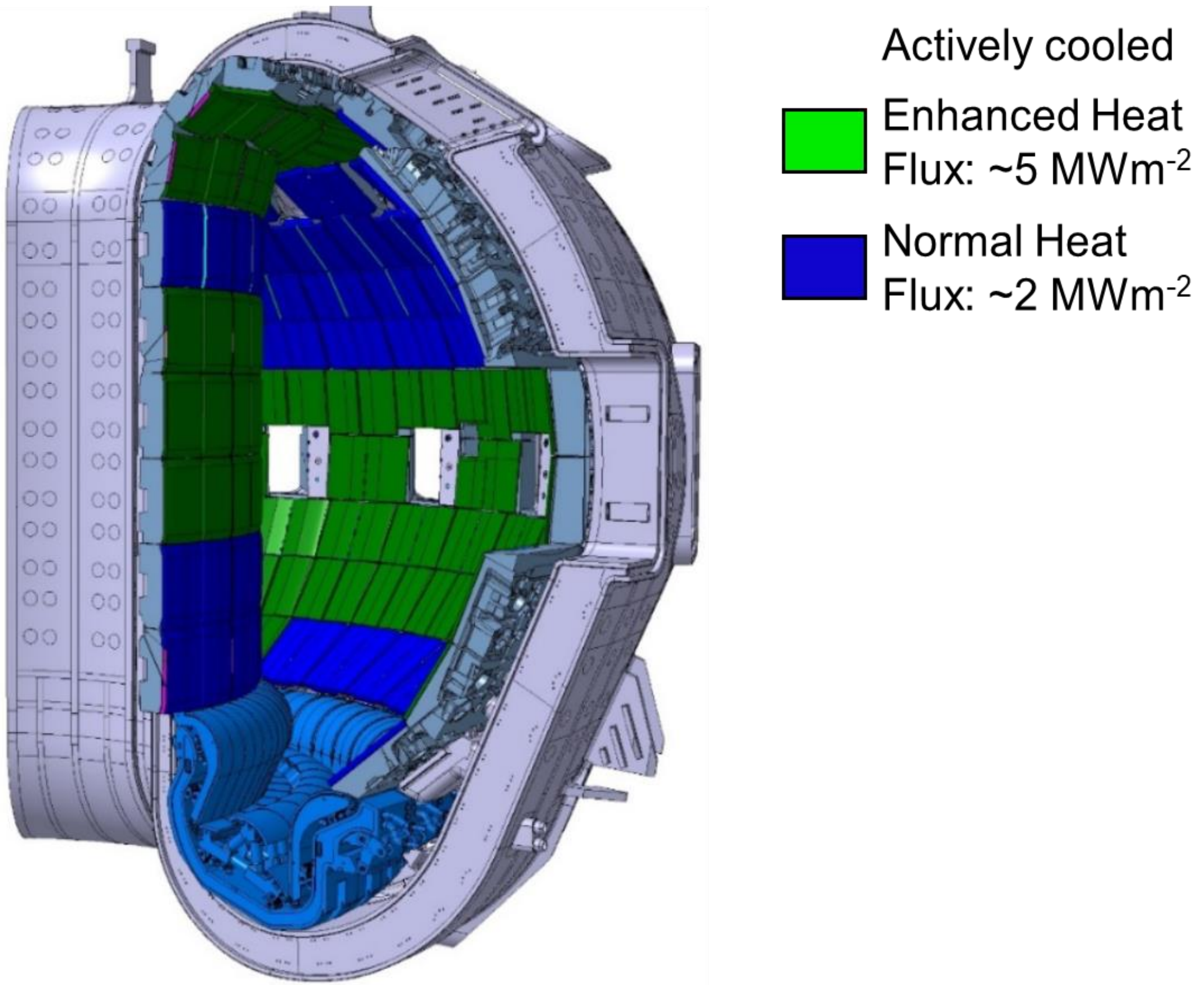
- Physics basis for tokamak operation with W walls is much stronger than it was at start of ITER construction
- Several issues with Be as PFC:
  - Erosion lifetime
  - Tritium retention in co-deposits
  - Low melting point → lower margin in I_p before potential "gap bridging" on FW panels (disruption current quench)
- Major benefit in assembly complexity and avoid costly later wall changeout
- BUT: lose low Z material facing the plasma and gettering properties of Be → boronization



First Wall Strategy

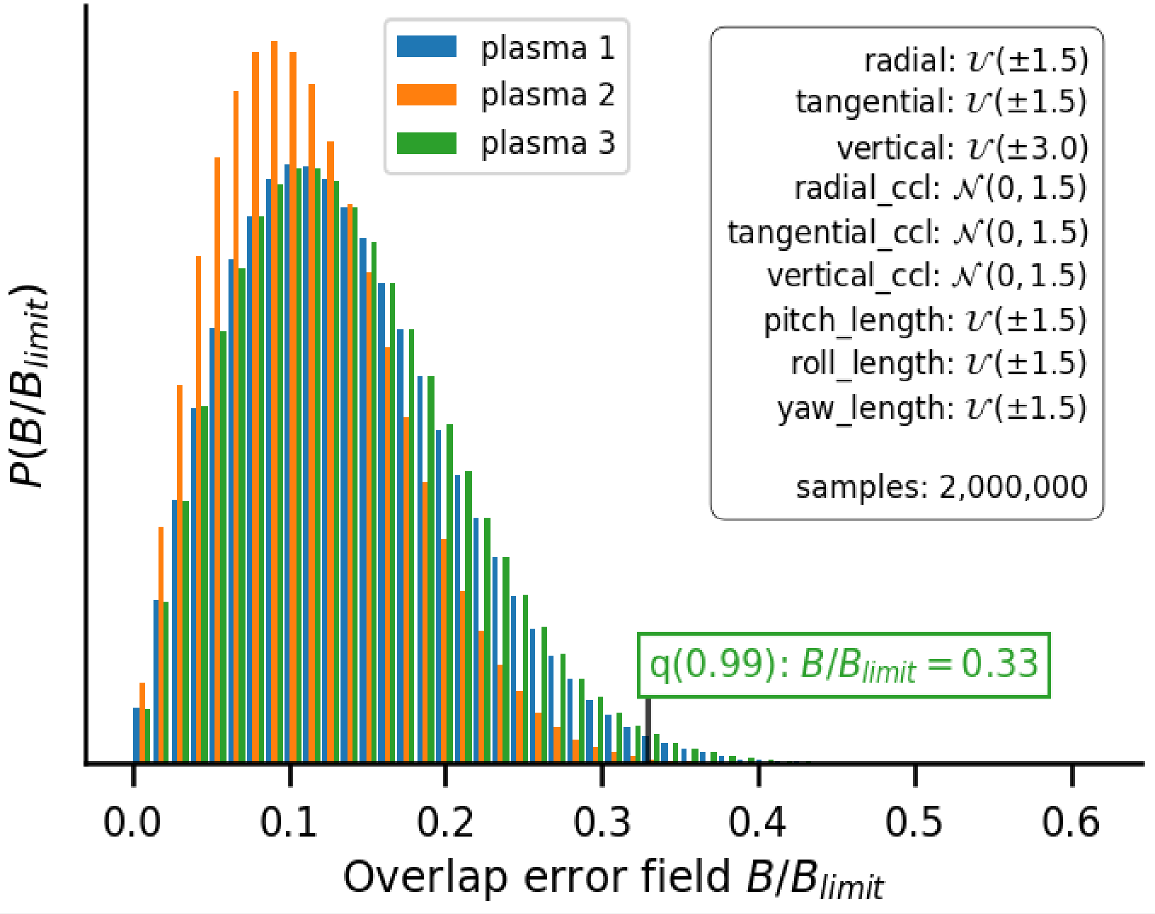
- Install full blanket shield and a provisional W plasma-facing surface but all inertially cooled
- Use SRO phase to learn:
  - Especially disruption load validation and mitigation (including runaway electrons) – without damaging final FW panels and avoiding water leaks
- Actively cooled, final brazed bulk W FW panels
- W armour thickened (8 mm (Be) → 12 mm (W)) in locations prone to runaway electron impact

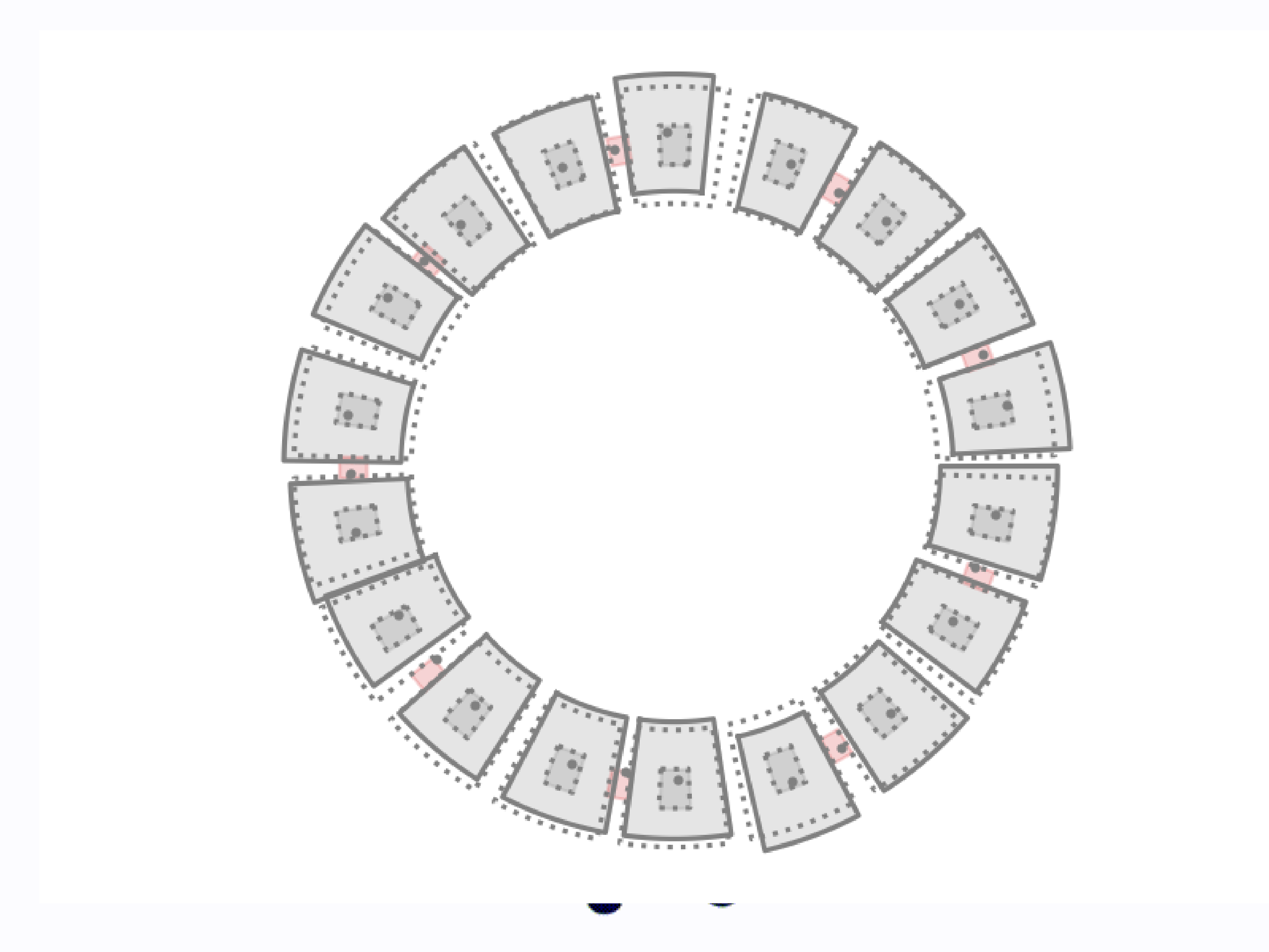
DT-1,2: Final First Wall



Assembly guided by physics → magnetic field symmetry essential !

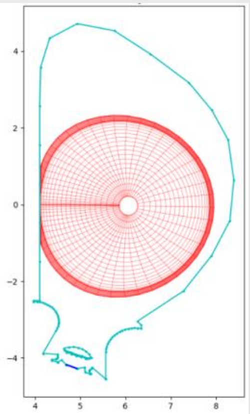
- **Magnetic field symmetry essential for high pressure → P_{fusion} ~ pressure ^{2}**
- **Sub-millimetric alignment of components essential (22°C → -269°C + $F_{magnetic}$)**



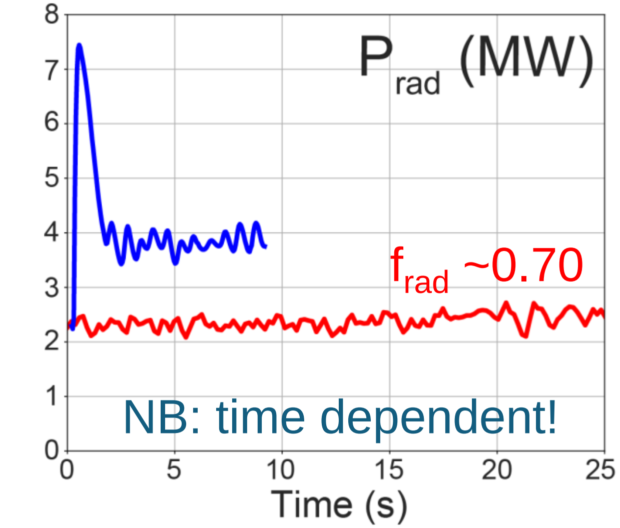


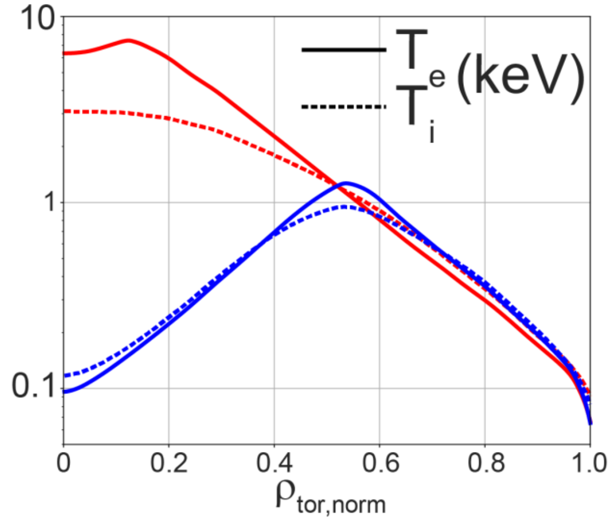
Integrated modelling

- SOLPS-ITER: good for 2D W source, but time independent
- DINA: time dependent but simple core transport model
- First attempts at JINTRAC core-edge integrated simulations
  - JETTO-SANCO + EDGE2D-Eirene
  - Core transport: TGLF-SAT2 + NEO
  - W bundling with 6 superstates



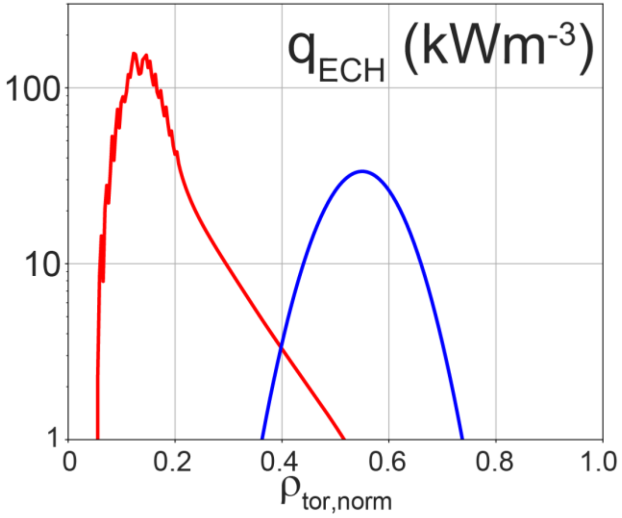
- Same P_{SOL} self-regulation found
  - Good agreement with SOLPS-ITER for same input
  - Consistent core-SOL solutions with no core W accumulation if central EC power deposition

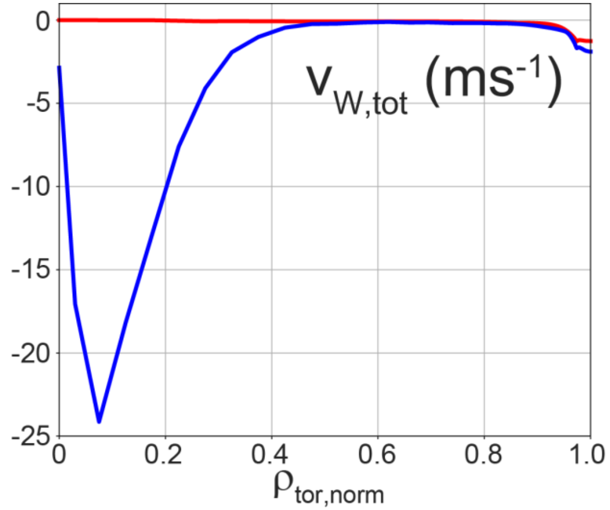




Red: central ECH
Blue: ECH shifted to off-axis at t = 0

Off-axis ECH → large increase in inwards W neo-classical transport



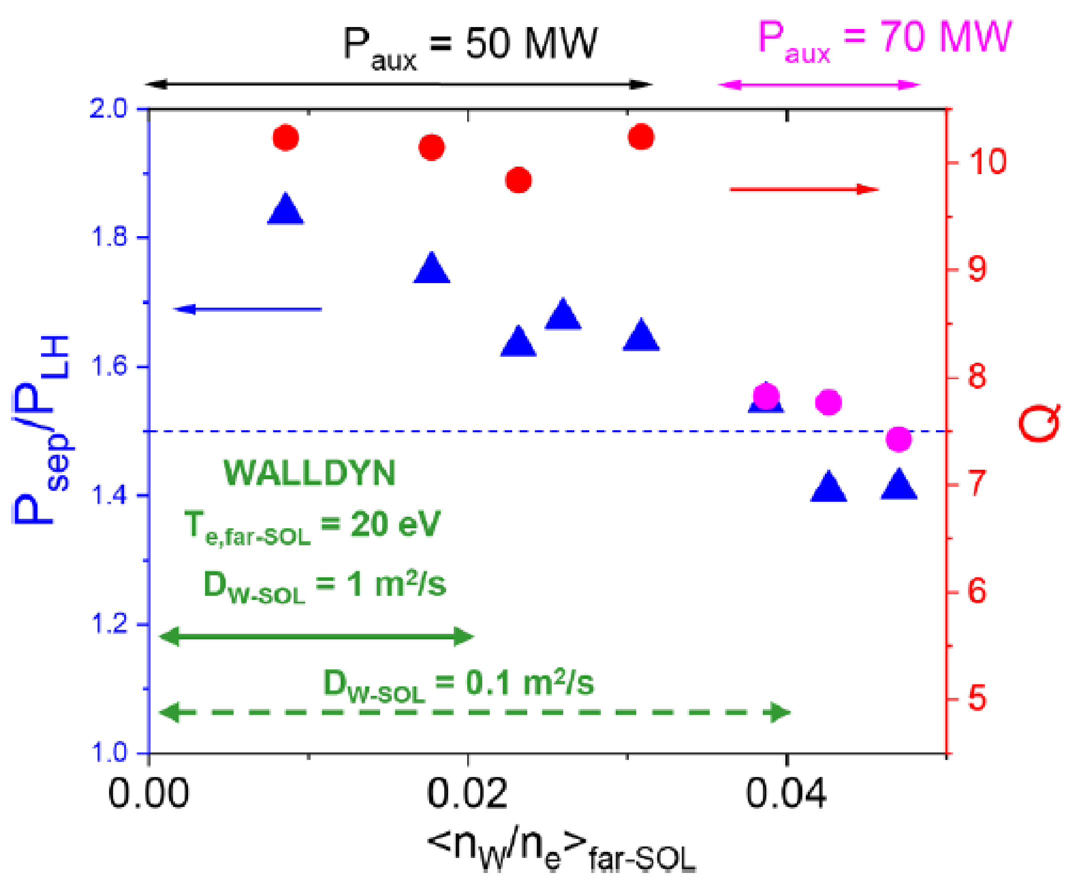


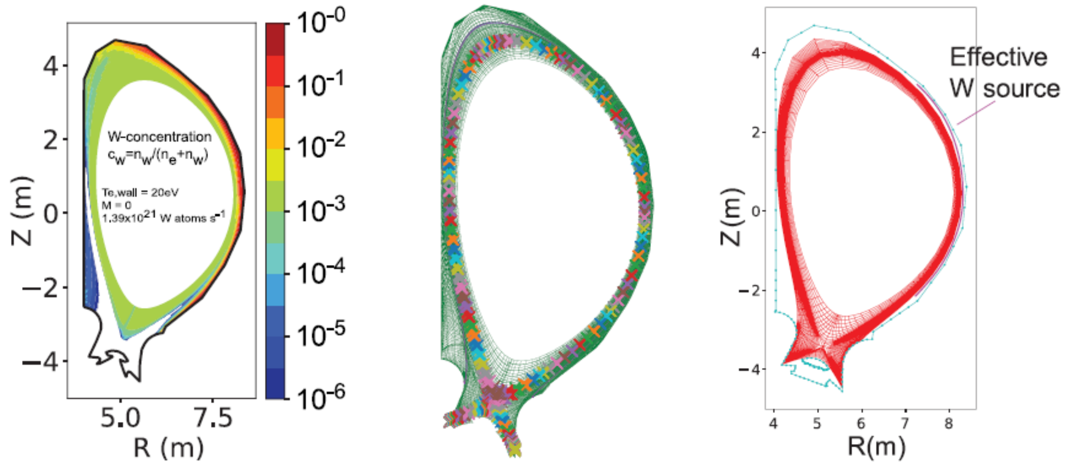
ITER, P_{IN} = 3.3 MW, I_p = 2.0 MA, B_T = 5.3 T

A. Loarte et al., PPCF **67** (2025) 065023

Impact of a W First Wall on Q = 10 target

- WallDYN2D W source calculated for range of Q = 10 background plasmas (SOLPS-OEDGE)
  - Wall source 4.5 – 26 x 10^{20} atoms s^{-1}
  - W source dominated by Ne + W self-sputtering (CXN sputtering negligible)
- → effective W source for JINTRAC modelling (TGLF-SAT2 core transport)
  - Q = 10 ok even with > 2x worst case W source
  - Uncontrolled W peaking not found in ITER high Q plasmas → W core transport in ITER dominated by turbulence, unlike in current devices (higher collisionality, stronger rotation)
  - Pedestal W screening for n_{sep} > 0.4 n_{GW}





Revised Research Plan and main elements

Summary of 2024 Baseline phases

Now		~18 months	27 months		~10 months
Engineering fabrication of system	Pre-SRO assembly	Integrated Commissioning I	Start of Research Operation (SRO)	Post SRO Assembly	Integrated Commissioning II

Install:
- Actively cooled W divertor
- Blanket shield blocks
- Inertial W First Wall panels
- 40 MW ECH
- 10 MW ICH

- Commission PCS and Protection Systems to reduce risks in DT-1
- Hydrogen L-mode to 15 MA/5.3T
- Demonstrate H-mode DD plasmas
- First assessment of boronization, fuel retention/recovery, ICWC

- Final, actively cooled W First Wall
- NBI: 33 MW
- ECH: 40 → 60-67 MW
- ICH: 10 → 20 MW
- Final diagnostics set

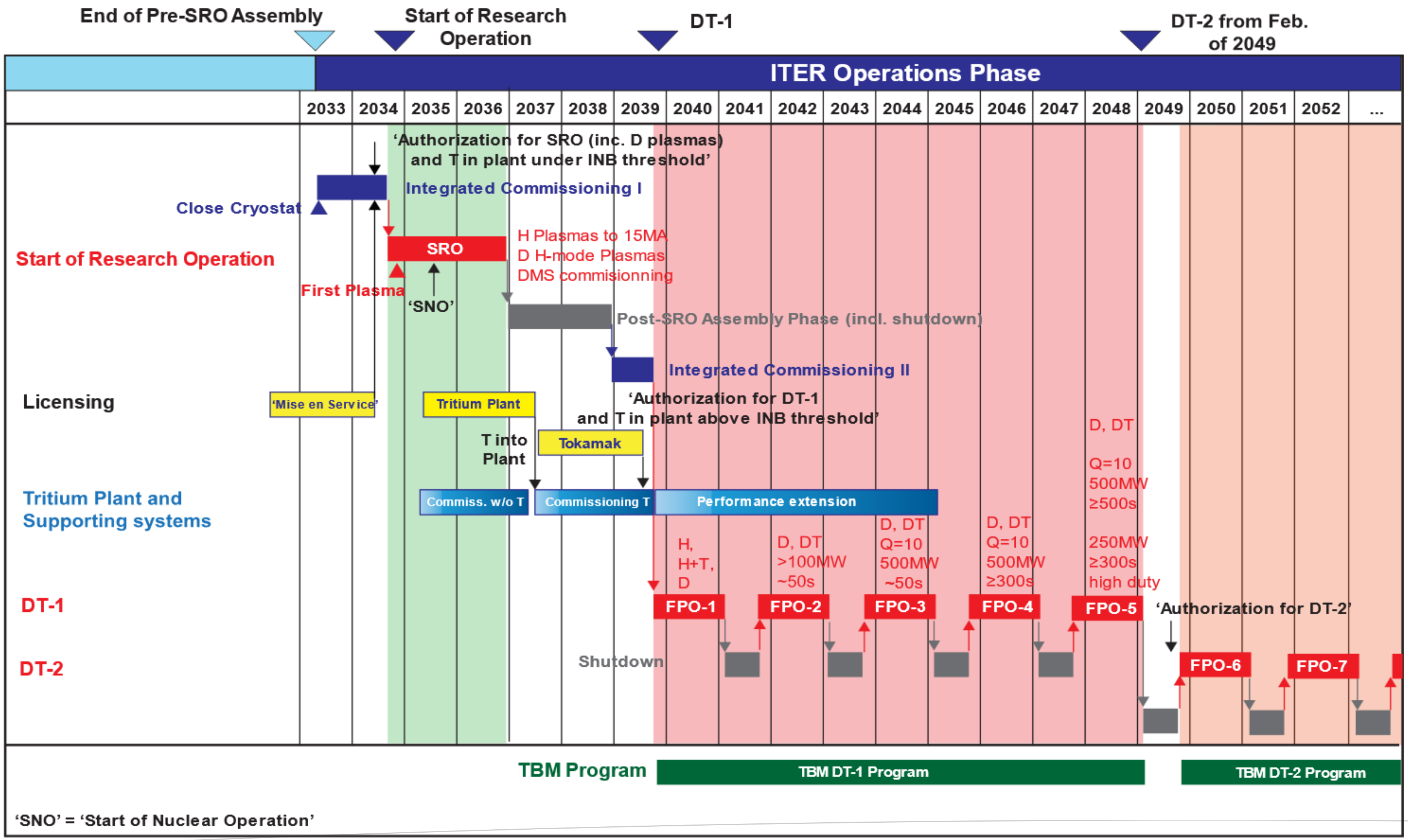
DT-2: 3 x 10^{27} neutrons

FPO-y	FPO-(...)	FPO-x
DT (Q=10), high duty, ≥ 500 s Q ≥ 5, 1000, 3000 s		

DT-1: ~9 years, 3 x 10^{25} neutrons

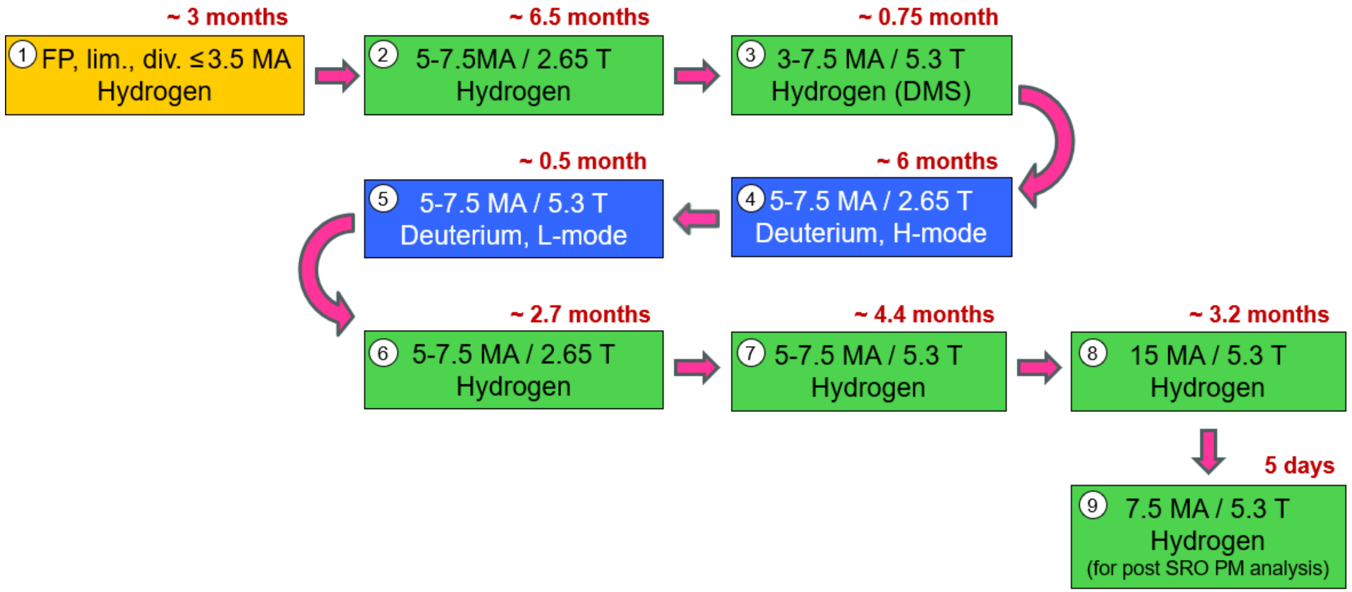
FPO-5	FPO-4	FPO-3	FPO-2	FPO-1
D, DT (Q=10),≥500 s High duty, 250 MW, ≥300 s	D, DT (Q=10) 500 MW, ≥ 300 s	D, DT (Q=10) 500 MW, ~50 s	D, DT 100 MW, ~50 s	H, H+T D

Summary of 2024 Baseline phases

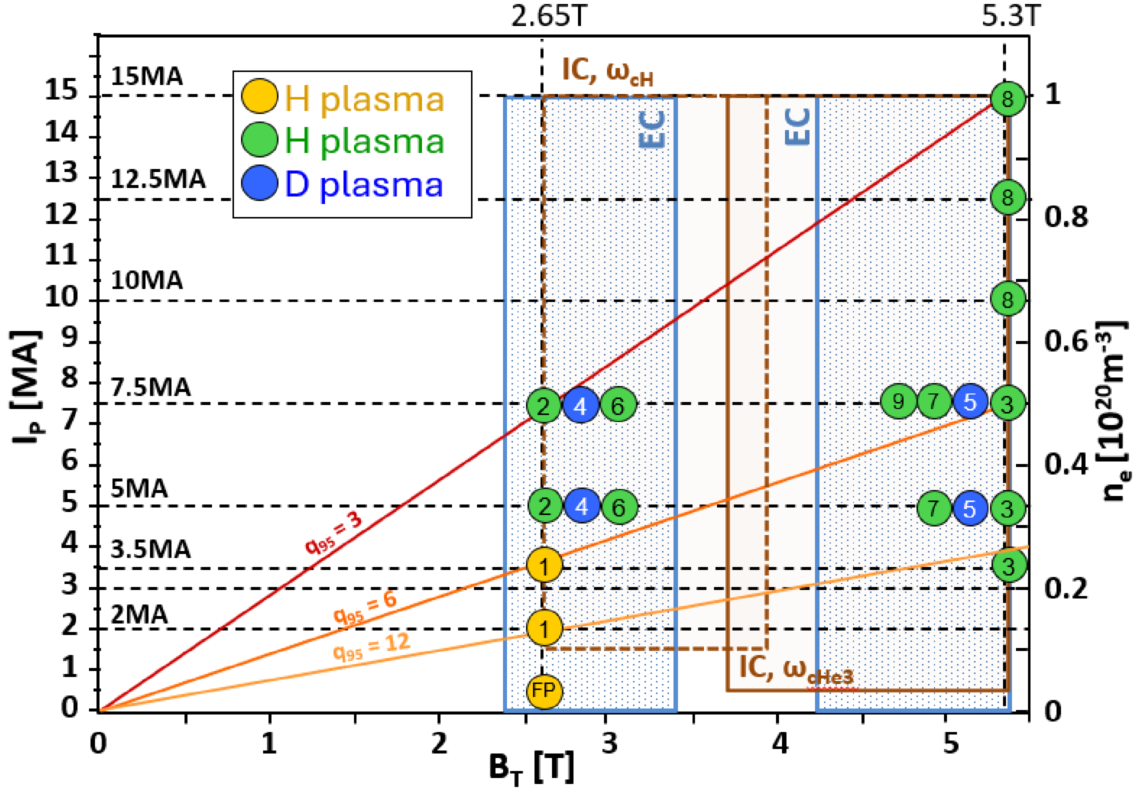


Detailed revised Research Plan now completed

- Use of W wall requires B_T values that provide effective central heating → scenario development at 2.65 T & 5.3 T in SRO and DT-1

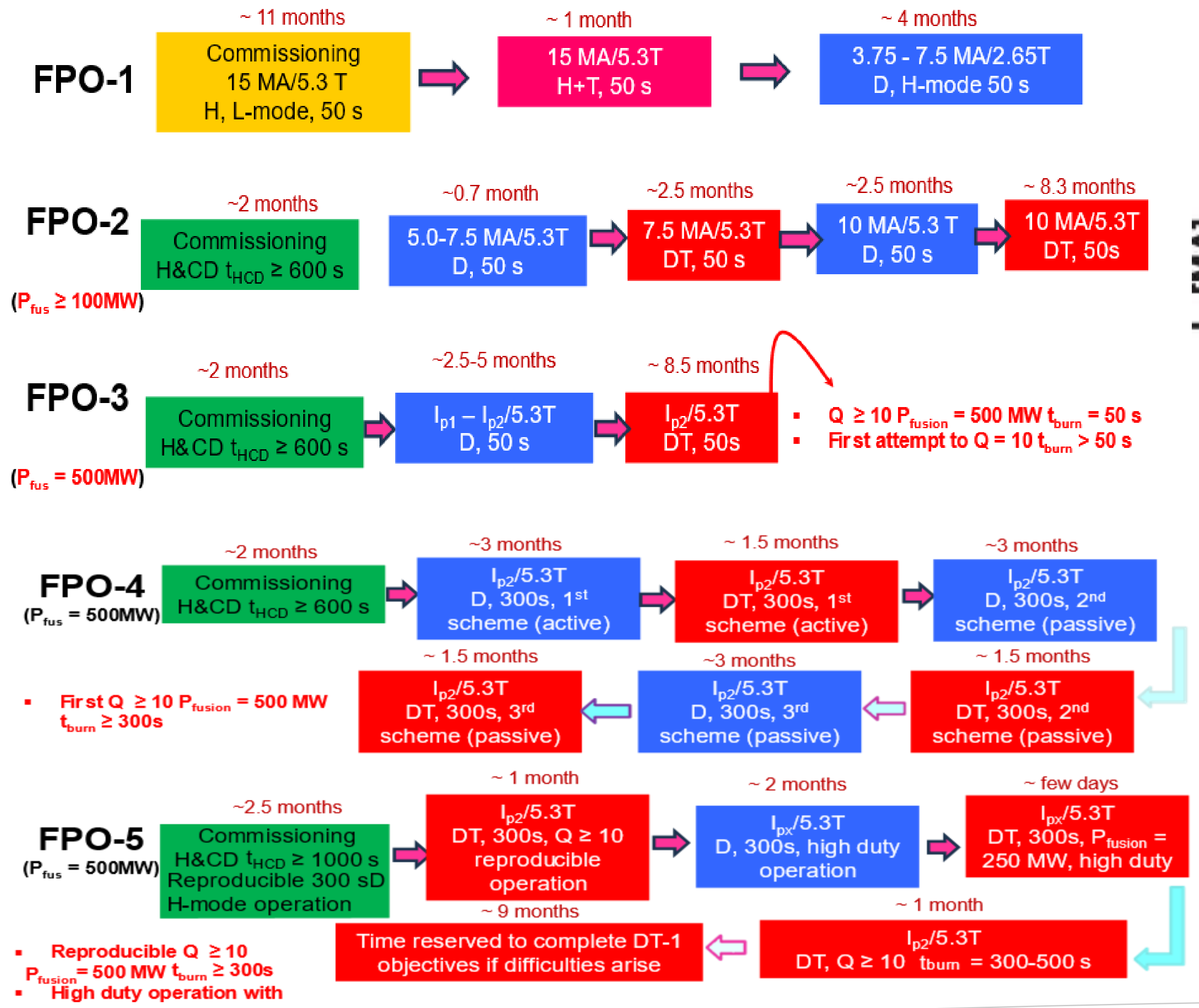


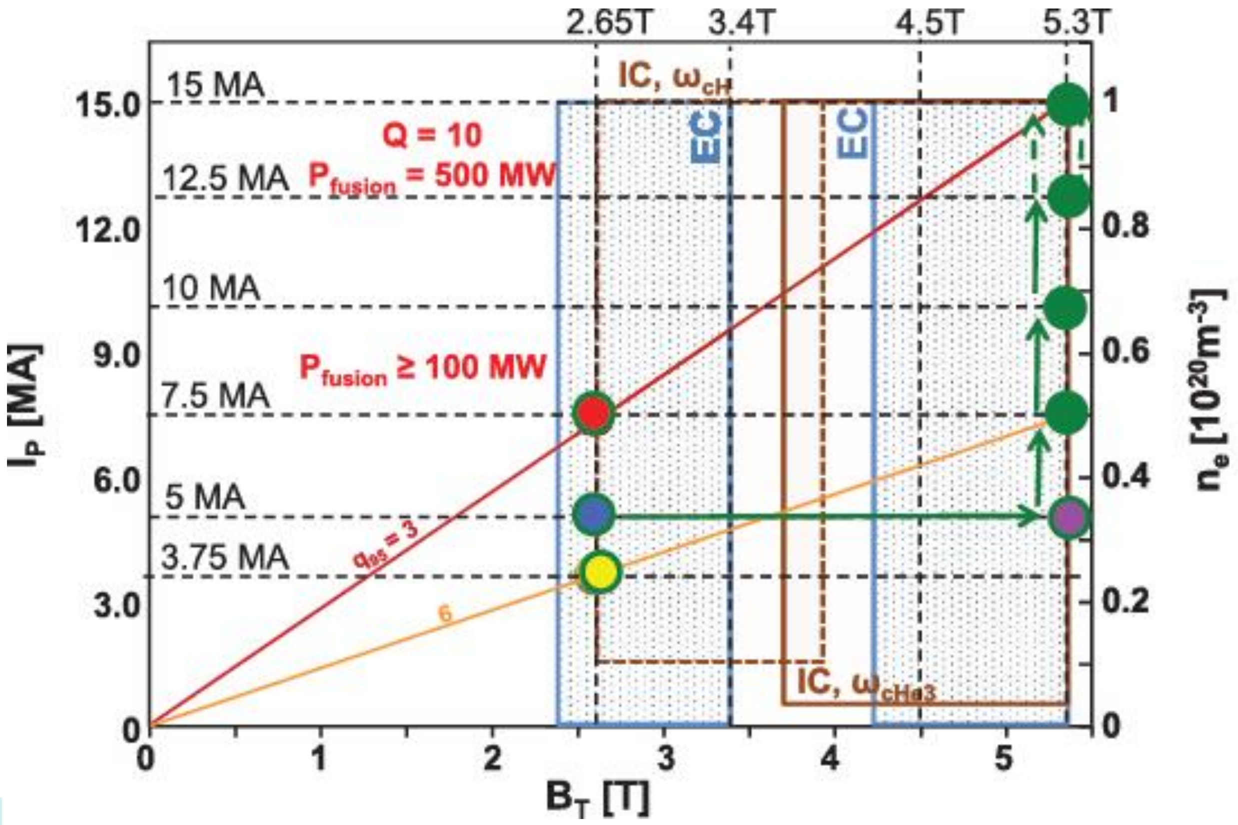
Example for SRO Phase



Sequence of L-mode scenarios to be explored in SRO (assuming n_e ~ 42% of Greenwald limit)

Research Plan for DT-1



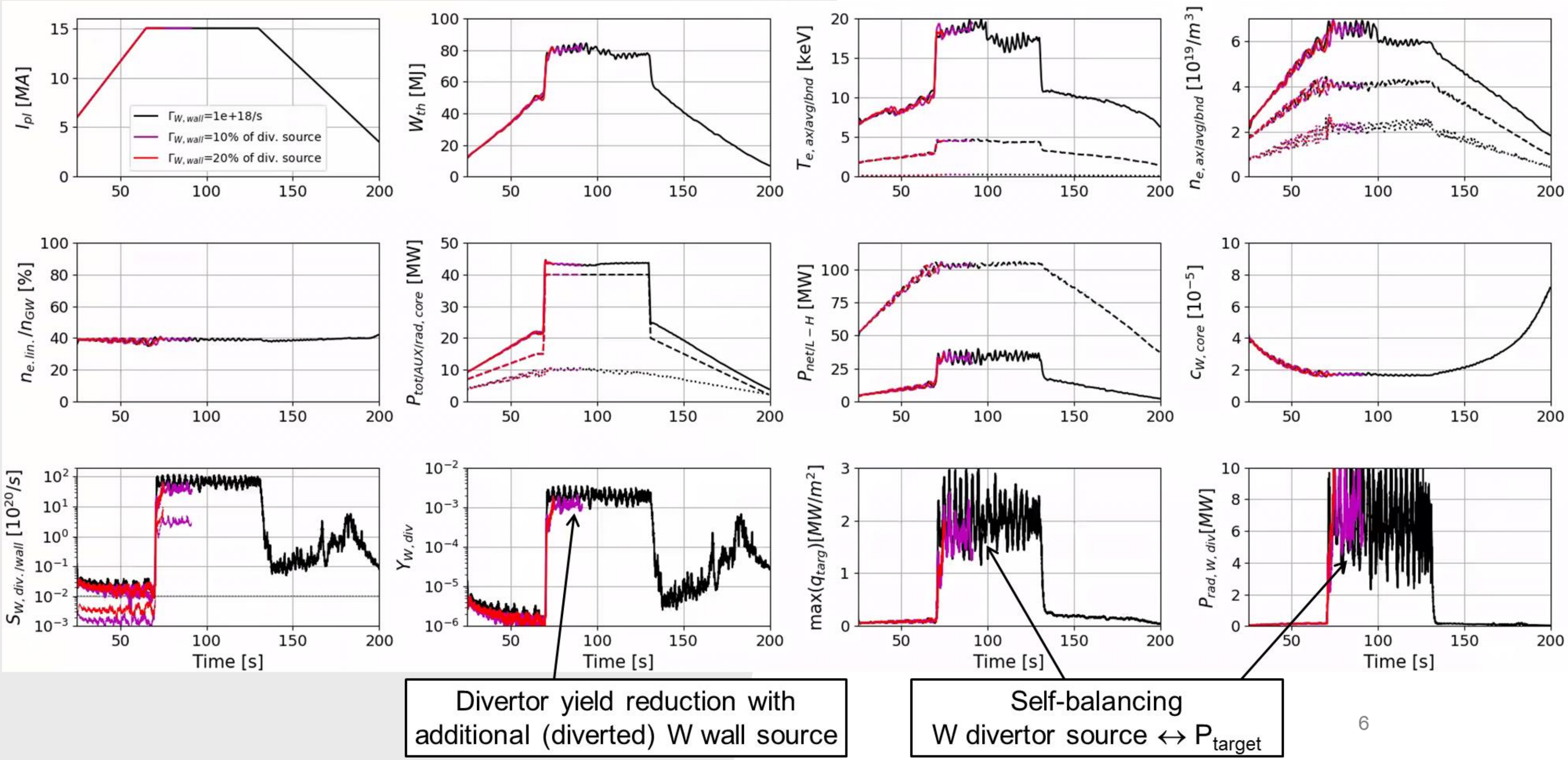


Sequence of H-mode scenarios to be explored in D and DT plasmas in DT-1 (assuming n_e ~ 85% of Greenwald limit)

- 3.75MA / 2.65T in DD
- 5 MA / 2.65 T in DD
- 7.5 MA/2.65 T in DD
- 5 MA/5.3 T in DD
- 7.5 → I_p ≥ 12.5 MA/5.3 T in D and DT

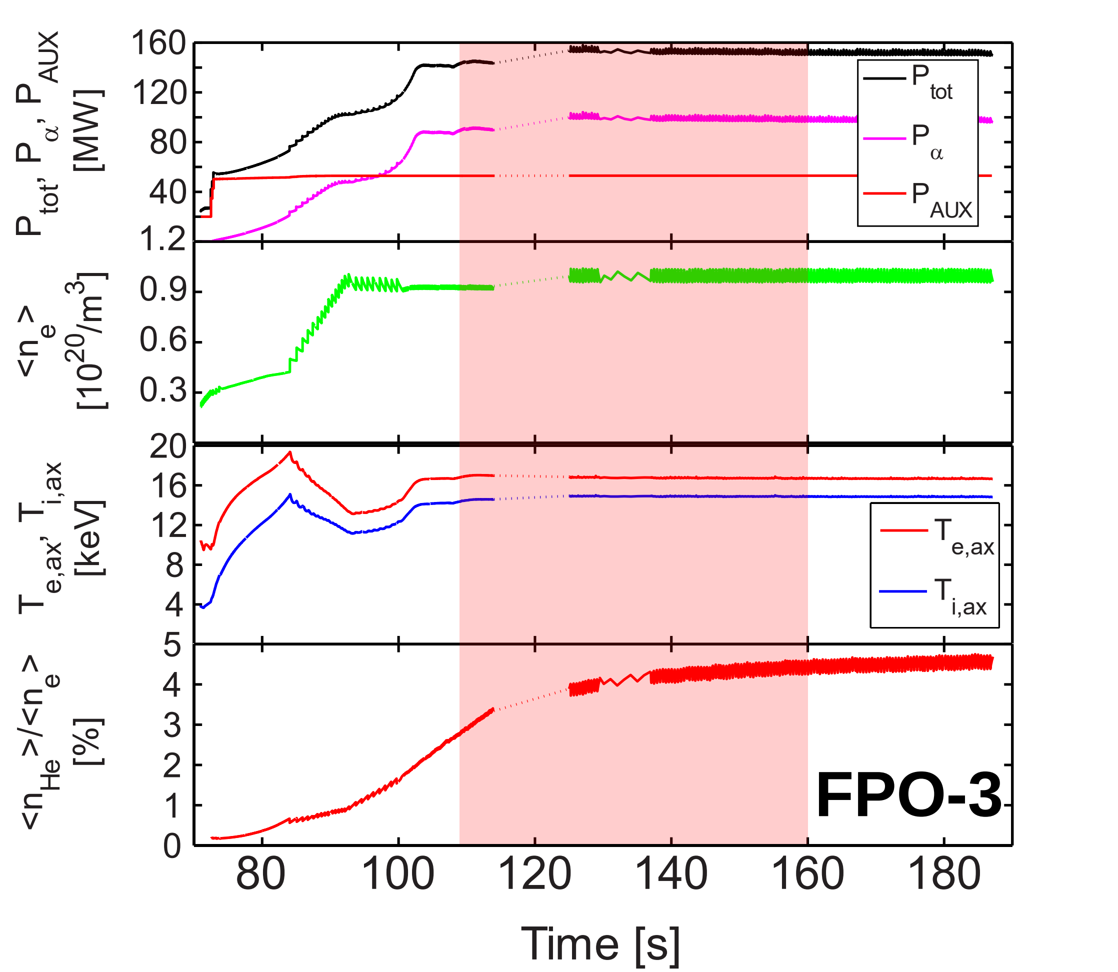
Assessment of scenarios with integrated modelling

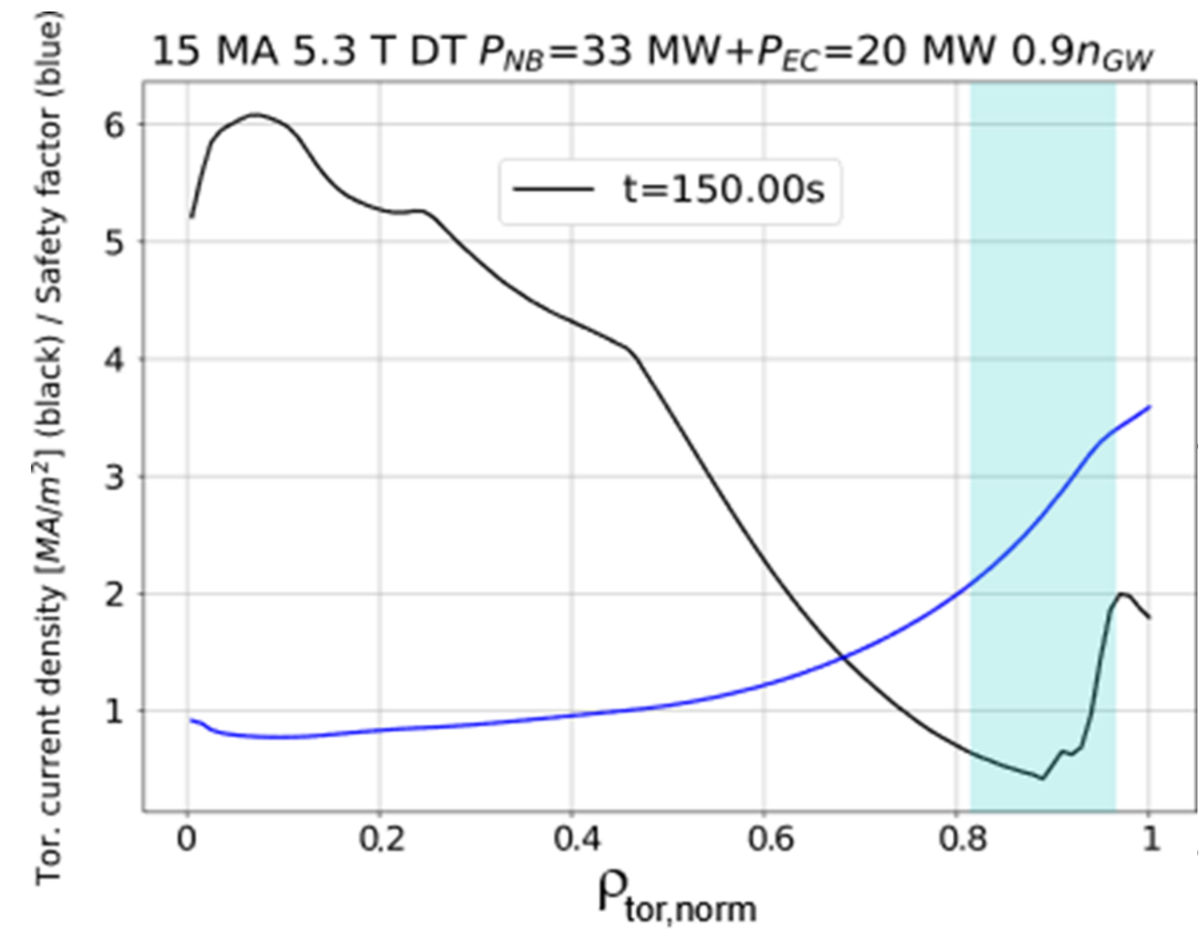
- **15 MA/5.3 T L-mode H scenario in SRO**



Assessment of scenarios with integrated modelling

➢ **15 MA/5.3 T Q = 10 scenario**





Conclusions

- ITER aims to demonstrate the integration of physics and engineering required for fusion to be an energy source for humankind (i.e. to build fusion reactors)
- Construction of the ITER and commissioning of ancillary systems is making good progress after overcoming difficulties in the last years
- To minimize impact of delays a “new baseline” has been developed. Re-optimized experimental plan to provide a robust approach to DT operation and Q = 10 → takes advantage of more available ancillary systems than in the original plan
- Research Plan developed in detail. Plan aims to be realistic/robust → retirement of risks as soon as possible with minimum impact and no success ensured at first try
- Some details of Research Plan will change as R&D on open issues advances
- Extensive use of integrated modelling to support the new baseline and Research Plan → Validation of models and tools to predict ITER plasma behaviour and planning of experiments in essential for efficient implementation of Research Plan
- Support by Members’ fusion researchers is essential for ITER’s success

Thanks for your attention !

iter
china eu india japan korea russia usa

New Baseline publications

Nuclear Materials and Energy 42 (2025) 101854

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Plasma-wall interaction impact of the ITER re-baseline☆

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https://www.sciencedirect.com/science/article/pii/S2352179124002771?via%3Dihub

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Plasma Physics and Controlled Fusion

Plasma Phys. Control. Fusion 67 (2025) 065023 (60pp)

https://doi.org/10.1088/1361-6587/add9c9

The new ITER baseline, research plan and open R&D issues

A Loarte[1,*], R A Pitts[1], T Wauters[1], I Nunes[1], P de Vries[1], S H Kim[1], F Köchl[1], A Polevoi[1], M Lehnen[1,27], J Artola[1], S Jachmich[1], A Pshenov[1], X Bai[1], I S Carvalho[1], M Dubrov[1,2], Y Gribov[1], M Schneider[1], L Zabeo[1], X Bonnin[1], S D Pinches[1], F Poli[1], G Suarez Lopez[1], M Merola[1], F Escourbiac[1], R Hunt[1], L Chen[1], D Boilson[1], P Veltri[1], N Casal[1], M Preynas[1], A Mukherjee[1,28], W Helou[1], F Kazarian[1], S Willms[1], I Bonnet[1], R Michling[1], L Giancarli[1], J van der Laan[1], M Walsh[1], V Udintsev[1], R Reichle[1], G Vayakis[1], A Fossen[1], M Turnyanskiy[1], A Becoulet[1], Y Kamada[1], G Zhuang[3], G Xu[4], X Gong[4], J Huang[4], M Jia[4], R Ding[4], J Qian[4], Y Sun[4], Q Yang[4], L Zhang[4], M Xu[5], L Zhang[5], S Brezinsek[6], J Stober[7], J Hobirk[7], F Rimini[8], J Garcia[9], S L Rao[10], J Ghosh[11], D Sharma[11], B Magesh[10], R P Bhattacharya[11], G Matsunaga[12], H Urano[12], T Hirose[12], K Ogawa[13], G Motojima[13], C K Sung[14], H H Lee[15], J K Park[16], M S Cheon[15], Y M Jeon[15], S Konovalov[2], S Lebedev[17], N Kirneva[2], Y Kashchuk[18], N Bakharev[17], X Chen[19], A Bortolon[20], L Casali[21], R Maingi[20], F Turco[19], K Schmid[7], Y Liu[19], J R Martín-Solís[22], C Angioni[7], I Pusztai[23], D Fajardo[7], D Mateev[6], E Lerche[24], D van Eester[24], P Vincenzi[25,26], R Futtersack[8], V Bobkov[7] and L Colas[9]

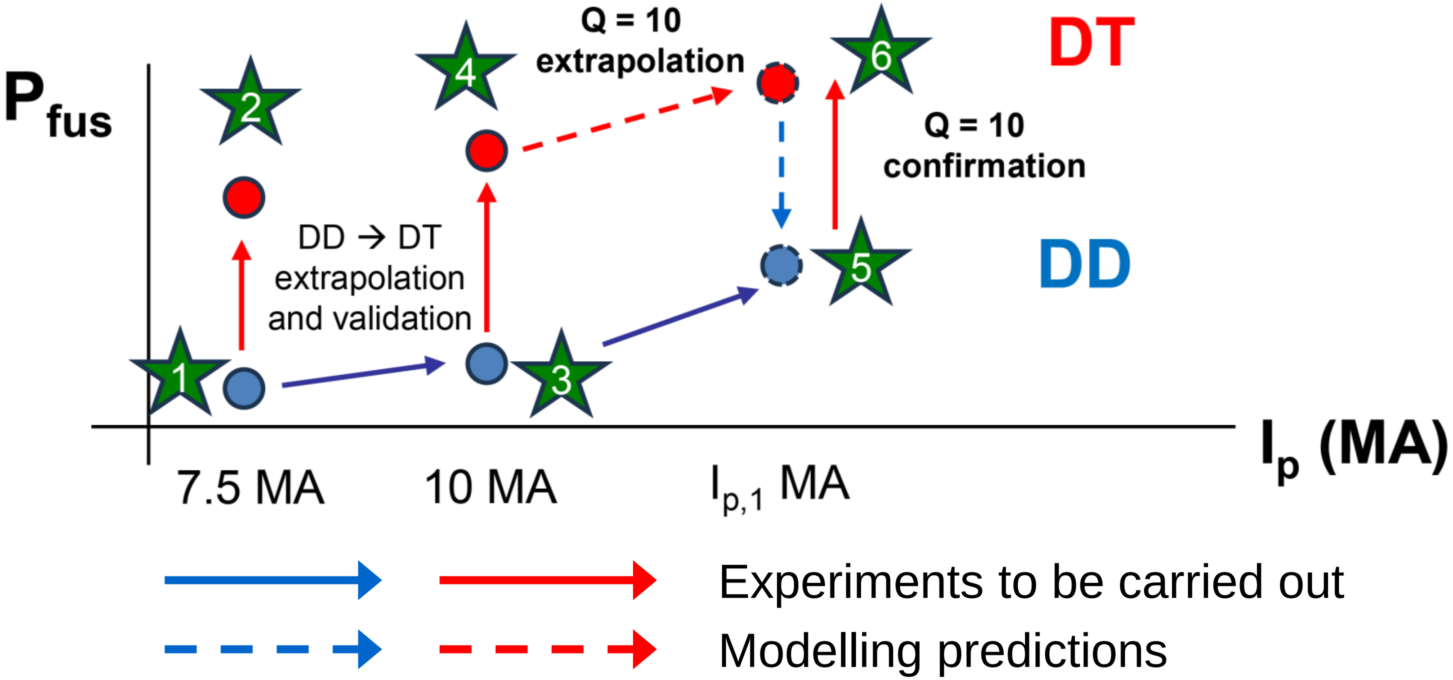
https://doi.org/10.1088/1361-6587/add9c9

- Technical report on R&D needs for the new Baseline ITR-2025-05
- New Research Plan in full detail to be published as Technical Report in few weeks

IRP strategy to Q = 10

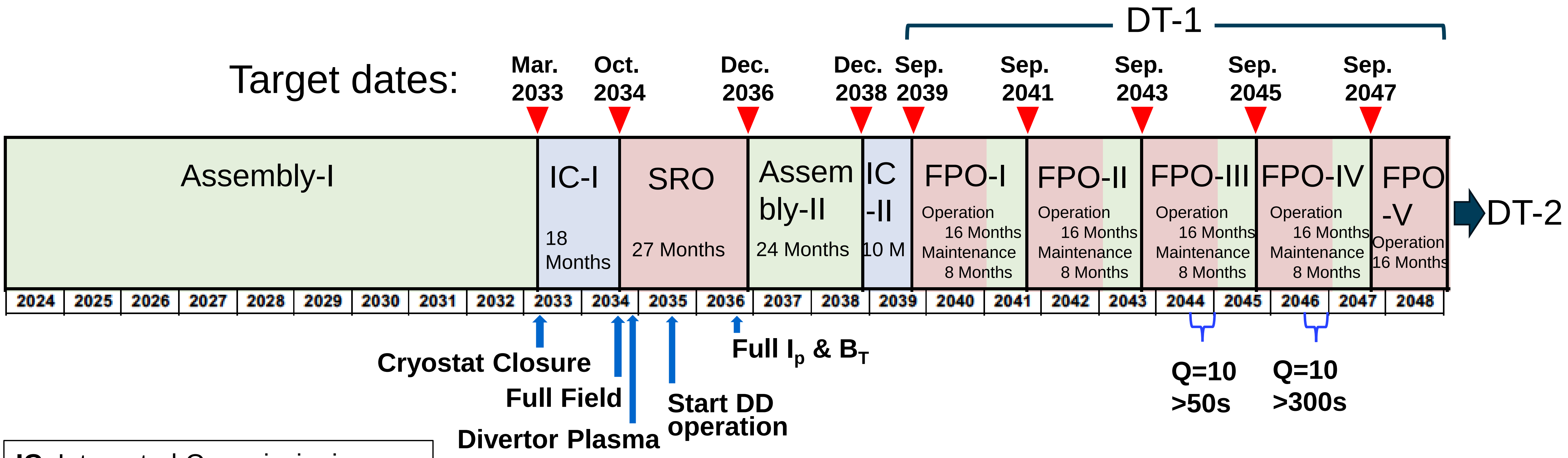
- Interleave D and DT plasmas to minimize use of neutron fluence
- Develop 50-50 DT H-mode scenarios using D and D + T (< 50%) H-mode scenarios
- Validate plasma models at lower (I_p, %T) ←→ predict next step and repeat
- Access to high P_{fusion} already from 7.5 MA/5.3 T if H_{98} > 1 at high q_{95}
  - Strategy used successfully in JET DTE-2 (e.g. J. Garcia NF 2023, C.F. Maggi NF 2024)

A. Loarte et al., PPCF **67** (2025) 065023



- DD and DT plasmas performed at lower I_p (Steps 1-4)
- Extrapolate by modelling to higher I_p to the level required to achieve Q ≥ 10 in DT (Step 6)
- Identify corresponding plasma parameters for DD (Step 5)
- Perform experiments in DD to verify Step 5 prediction
- If successful perform DT plasma

And finally: overall Project Schedule for new Baseline



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

- Approval chronology:
  - ITER STAC-30 (May 2024) endorses Level 1 Research Plan and proposed Level 1 Construction Schedule
  - ITER Council 35 (Nov. 2024) endorsed the overall approach proposed for the 2024 Baseline
  - ITER STAC-32 (May 2025) endorses Level 2 and Level 3 Research Plan → ITER Council 36 is this week!

Miscellaneous reserve material

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**

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https://www.sciencedirect.com/science/article/pii/S2352179124002771?via%3Dihub

- Technical report on R&D needs for the new Baseline just released as an ITER Report

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https://doi.org/10.1088/1361-6587/add9c9

Cryostat lower Thermal Shield repair also underway

- Support thermal shield panels being repaired and replaced – the easiest parts of the cryostat shield to access

26 Dec. 2024

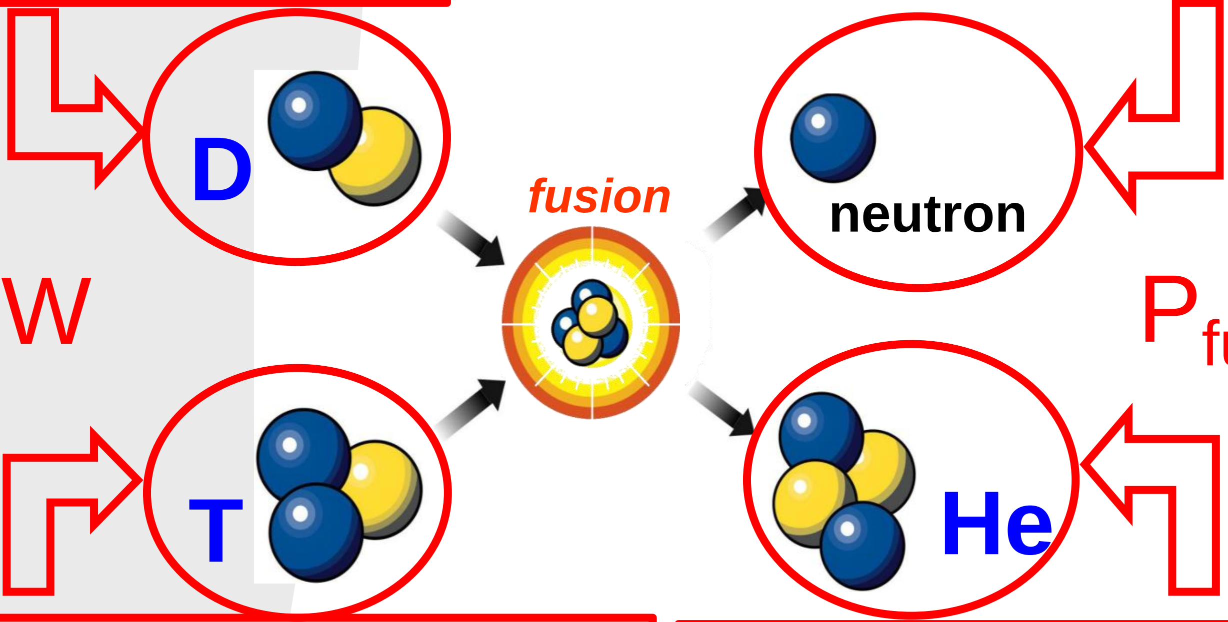
ITER Objective

Demonstrate the scientific and technical viability of f
source for humankind

Present in 1 part in 6500 in water (H_2O) – easy to extract

Escapes from plasma and deposits energy on the wall of the reactor

$P_{heat} = 50$ MW



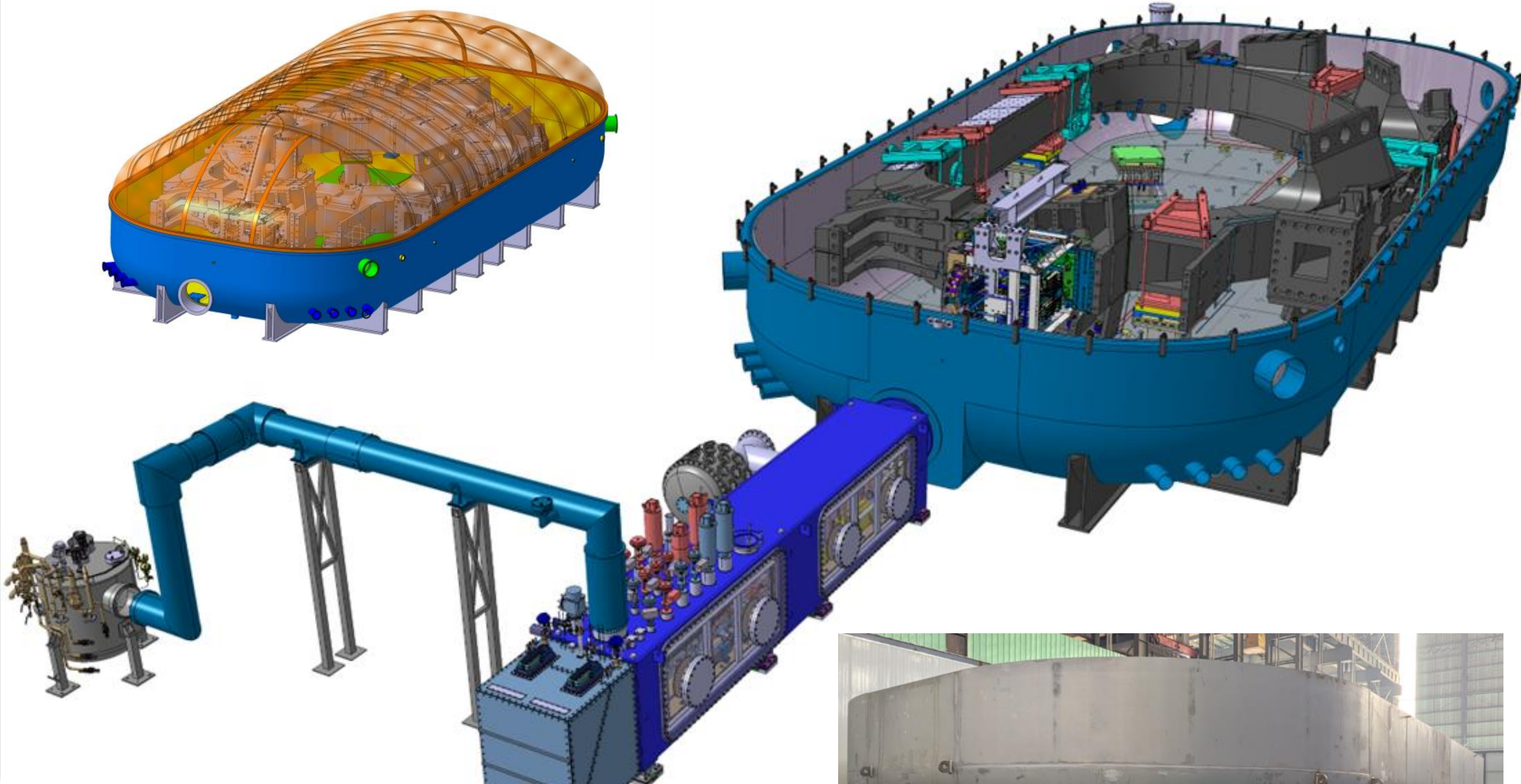
$P_{fusion} = 500$ MW

Does not exist in nature. Produced in the reactor (from Lithium) n + Li → T + ^{4}He

Charged Particle → trapped in magnetic fields re-heats DT

TF/PF cold testing

- New baseline includes mitigation for some of the superconducting magnet risks:
  - Cryostat to accommodate TF coils and PF1 coil
  - A complete unit for energization (up to 67 kA for TF coils) and associated Fast Discharge Unit
  - Connection to ITER's cryoplant using 1 of 3 He refrigerators (cool to 4 K)



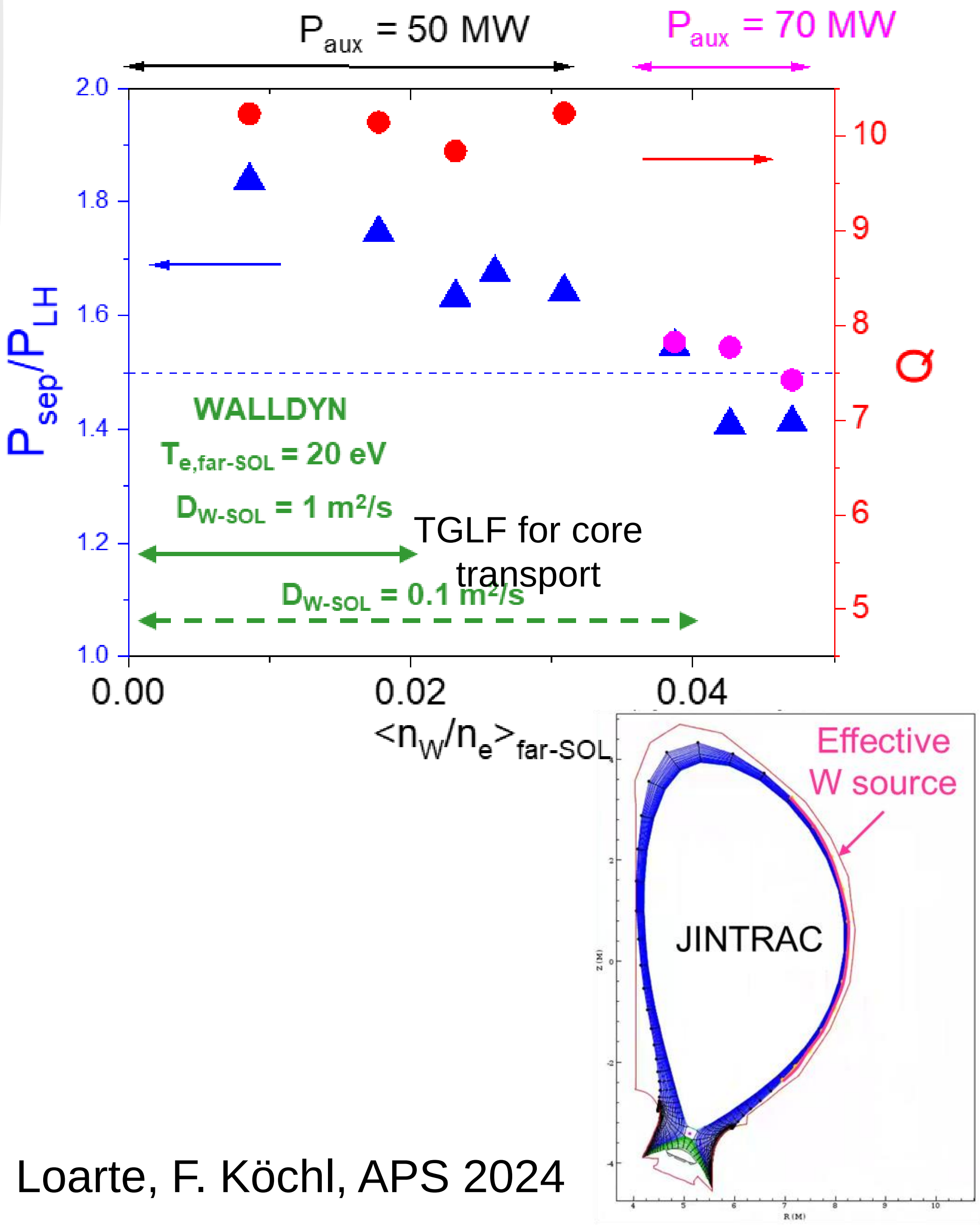
All being installed in PF winding building → start of operation scheduled for Dec. 2025

Cryostat base already completed in ASIPP/SENPEC (China)

Impact of a W First Wall on Q = 10 target

- Very recently re-calculated to fix some issues with WALLDYN (W atomic rates) and with TGLF-SAT2 core transport model
- Result essentially unchanged
  - W core transport in ITER dominated by turbulence, unlike in current devices (higher collisionality, stronger rotation)
  - Pedestal W screening for $n_{sep} > 0.4\ n_{GW}$

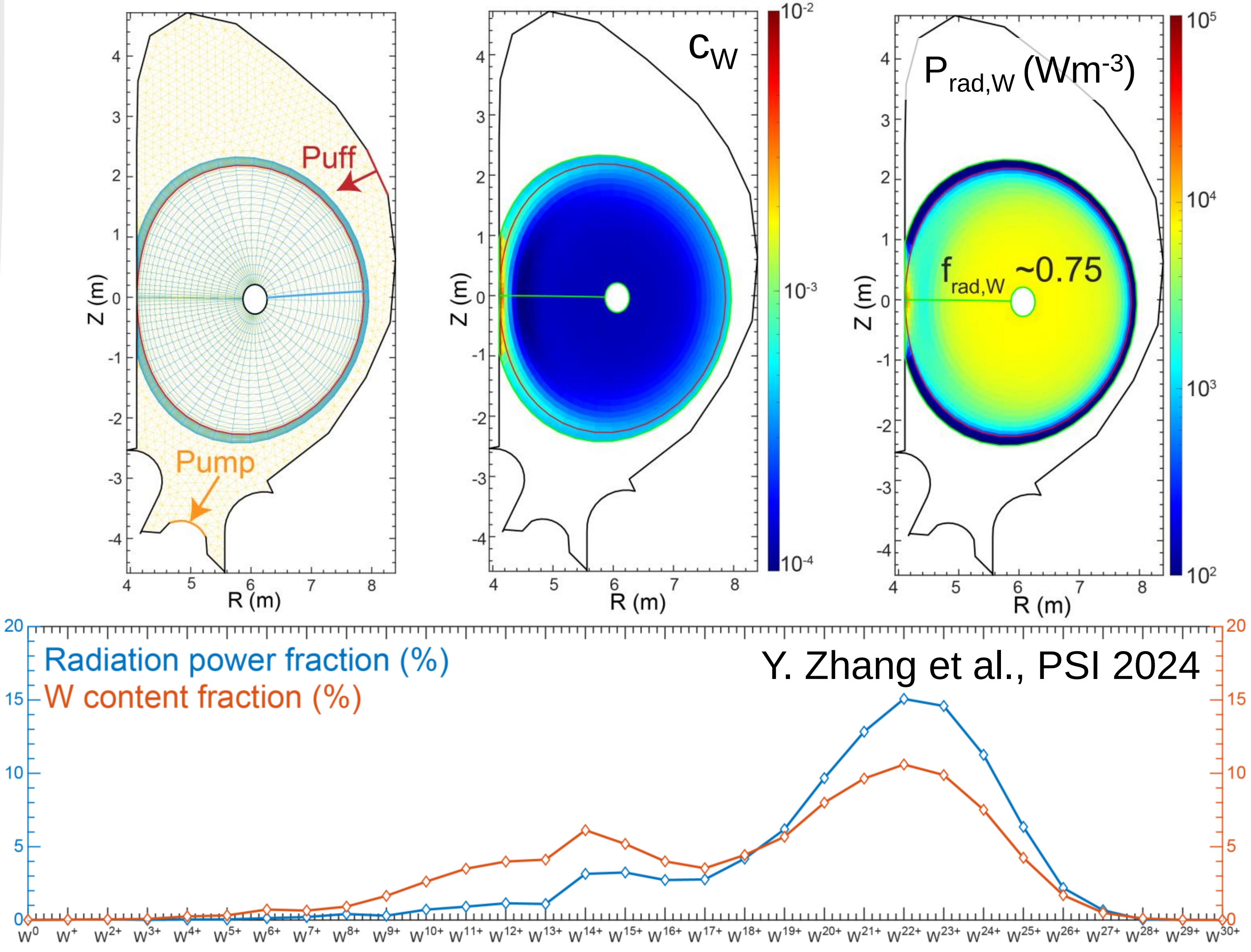
- NB: H-mode access with the W wall requires sufficient power in reserve if radiation losses are high (α-heating needs to build-up)



A. Loarte, F. Köchl, APS 2024

SOLPS-ITER, limiter plasmas and W

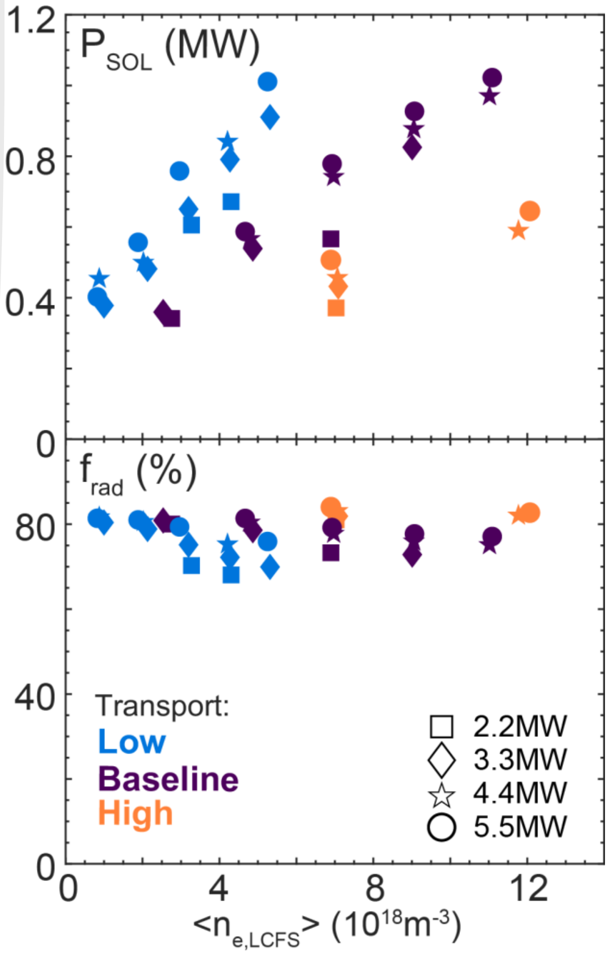
- First attempts to model ITER limiter phase
- Simulation database (I_p, n_e, P_{ECH}, $D_{\perp,SOL}$, $\chi_{\perp,SOL}$)
  - Stationary simulations – single time point in DINA current ramp
  - Hydrogen plasma
  - Numerical grid to core
  - Including sputtered W (up to W^{30+} followed)

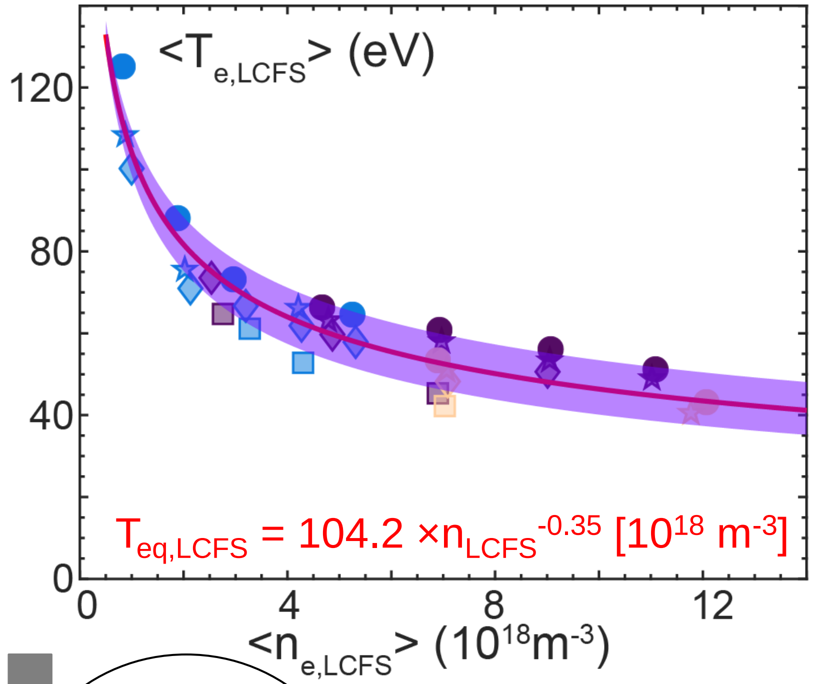


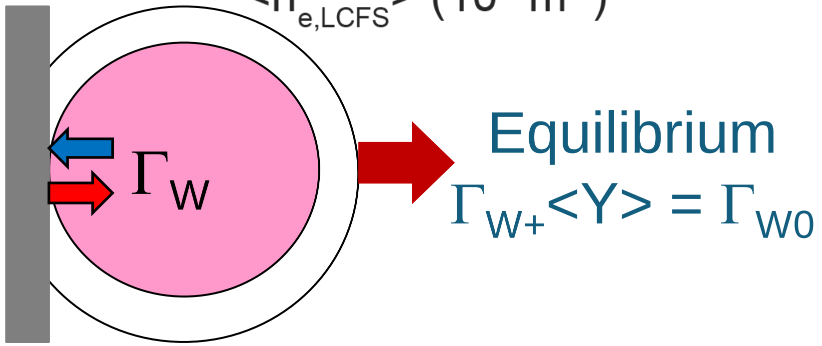
Example at P_{IN} = 3.3 MW, I_p = 2.0 MA, B_T = 5.3 T, $n_{e,LCFS}$ = 2 x 10^{18} m^{-3}

Self-regulating system

- f_{rad} ~ 0.7÷0.9 independent of heating distribution or core transport
- Use database to obtain $T_{e,LCFS}$ ($n_{e,LCFS}$) as boundary condition for 1.5D DINA scenario code → more realistic W source
  - Good experimental evidence that this occurs from EAST
  - Further expts. **now** on ASDEX-Upgrade, WEST
  - ITER modeling has been further extended (to be subm. to NF)





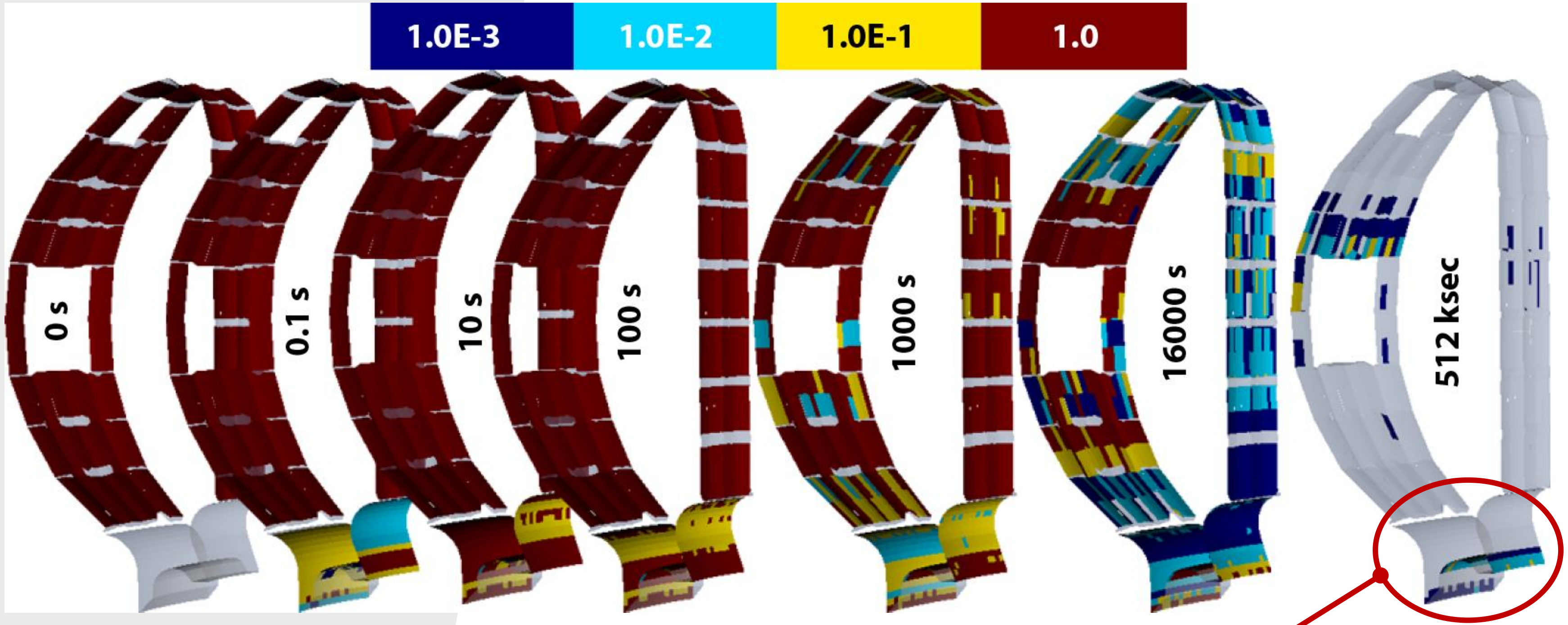


Always an equilibrium SOL solution with $\langle Y_{W\text{-}W} \rangle = 1$ which constrains P_{SOL} and determines the core W content required to dissipate ($P_{IN} - P_{SOL}$)

Y. Zhang et al., PSI 2024

Boron layer lifetime?

- How long might the gettering properties of the boron layer last → how often might ITER need to boronize?
- WallDYN3D with EMC3-Eirene plasma background
  - Trace B & W migration in 3D shaped wall
  - Case of "hot stagnant" far SOL
  - Initial 100 nm thick boron coating
  - Account for surface composition dynamics



Plasma wetted areas deplete rapidly (~1000 s) → deposition at divertor baffles → re-erosion → most boron ends up below inner divertor target → potential dust source

Gettering lifetime maybe several 10^4 seconds

K. Schmid, PSI 2024

SRO OBJECTIVES

- Commission control and protection systems with plasma up to 15 MA/5.3 T
- Demonstrate disruption mitigation up to 15 MA/5.3 T
- Develop plasma scenarios up to 15 MA/5.3 T in L-mode
- Develop plasma scenarios up to (at least) 5 MA/2.65 T in H-mode with DD plasmas within **1.5×10^{20} neutron fluence** (in-vessel human access after SRO)
- First assessment of fuel retention and removal efficiency (H → D → H)

- Successful SRO phase: ITER can reliably operate at its maximum I_p and B_T in L-mode and in H-mode at reduced levels (5-7.5 MA / 2.65 T) in DD plasma (marking start of nuclear operation)

DT-1 OBJECTIVES

- Commission control and protection systems with plasma up to Q = 10
- Demonstrate disruption mitigation up to Q = 10
- Develop plasma scenarios in DT up to 15 MA/5.3 T in H-mode (or at lower I_p if Q = 10 can be demonstrated) within ~3 x 10^{25} DT neutrons (e.g. ~550-600 pulses, Q = 10, 300 s burn)
- Study physics of burning plasma and their integration with all-W PFCs
- Address specific issues for development of the TBM programme, including high repetition operation with $P_{fus} \geq 250$ MW

- Successful DT-1 phase → ITER can achieve DT plasmas with dominant P_α and all required scenario integration and control issues can be maintained over time scales of 100's of seconds → Q = 10 goal and key information on upgrades and licence for DT-2

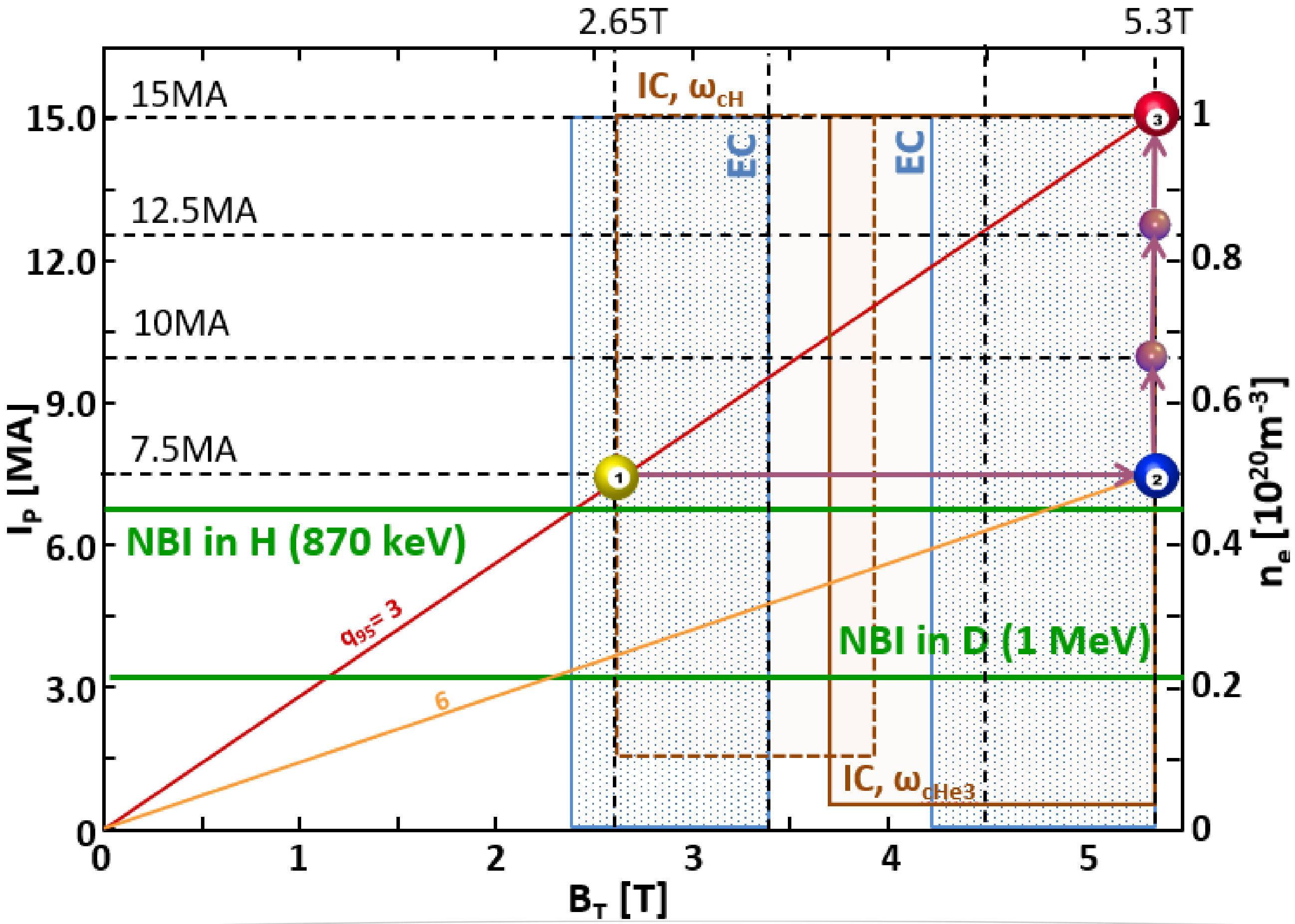
Strategy for achievement SRO objectives

- Develop L-mode scenarios to 7.5 MA/2.65 T in H (q_{95} = 3 - 6)
  - Commissioning with plasma (Plasma Control/Protection, ECH, diagnostics, DMS, …)
  - Characterize L-mode and first try to H-mode
- B_T = 5.3 T and explore high q_{95} operation in H (q_{95} = 6 -12)
  - Commissioning with plasma
  - Disruption load characterization before activation by DD and DMS demonstration
  - Characterize L-mode at high q_{95}
- Develop H-mode scenarios up to 7.5 MA/2.65 T in DD (q_{95} = 3 - 6)
  - Commissioning with plasma (+ ICH H-minority or $2\omega_D$, diagnostics, …)
  - H-mode scenarios up to P_{add} = 50 MW (P_{add}/P_{LH} (@$0.9n_{GW}$) ≥ 1.5)
  - Demonstrate T (D) removal strategy
- Complete hydrogen L-mode scenarios (7.5 MA/2.65 T) and expand to 15 MA/5.3 T
  - Commissioning with plasma (+ ICH ^{3}He-minority, …)
  - Disruption load characterization and DMS demonstration to highest W_{mag}

SRO H&CD scenario development pathway

- Use of W wall favours B_T values that provide effective central heating → scenario development at 2.65 T & 5.3 T in SRO and DT-1

- EC operation (up to 67 MW available):
  - 2.65T: X2 in L-mode, O2 in H-mode
  - 5.3T: O1
- IC operation (10 MW available):
  - 2.65T:
    - in D and DT: H minority or D 2nd harmonic majority
    - in H: no efficient scheme
  - 5.3T:
    - in D or H: ^{3}He min. at 53 MHz
    - in DT: ^{3}He min. followed by T maj. both at 53 MHz



M. Schneider

Overall SRO plan (includes FP demonstration)

~16 months

~3 months
Limiter, ~3.5 MA
Hydrogen

~5 months
5 MA / 2.65 T
Hydrogen

~1.5 month
7.5 MA / 2.65 T
Hydrogen

~0.75 month
3-7.5 MA / 5.3 T
Hydrogen (DMS)

Start of D campaign
~ 28 months after
cryostat closure

~4 months
5 MA / 2.65 T
Deuterium, H-mode

~2 months
7.5 MA / 2.65 T
Deuterium, H-mode

~10.5 months

~1 month
5 MA / 2.65 T
Hydrogen

~1.7 month
7.5 MA / 2.65 T
Hydrogen

~2.1 months
5 MA / 5.3 T
Hydrogen

~2.3 months
7.5 MA / 5.3 T
Hydrogen

~3.2 months
15 MA / 5.3 T
Hydrogen

Fluence in DD ~ 1.5×10^{20} neutrons to allow
in-vessel installation work post-SRO

Strategy for achievement of DT-1 objectives

- Develop L-mode scenarios (15 MA/5.3T) in H with new hardware & retire T risks
  - Commissioning with plasma (plasma control/protection, ECH/ICH/NBI, diagnostics, DMS, …)
  - Demonstrate PFC performance up to P_{add} ~ 100 MW
  - Demonstrate disruption mitigation by hot-tail + T-decay seeds to highest W_{mag}
  - Demonstrate T removal efficiency
- Develop DD at 2.65 T (q_{95} = 3 - 6) and then DD and DT at 5.3 T (q_{95} = 6 - 9) “short pulse” $t_{“burn”}$ ~ 50 s (~ n_{He} stationary) to Q = 10
  - Connect with SRO H-modes at 2.65 T to assess new H&CD impact
  - Develop H-mode scenarios at 5.3 T interleaving DD and DT plasmas → address high I_p/P_{tot} control and integration issues at each step in DD before DT
  - Gradual increase of W_{th}, W_{mag}, P_{fusion} and RE seeds to minimize disruption risks
  - Demonstrate Q = 10 at lowest possible I_p ($H_{98}(q_{95}>3)>1$) taking short pulse advantage
- Extend “Q = 10 scenario” to $t_{“burn”}$ ≥ 300 s in DD and then in DT
  - Apply active control schemes (e.g. ECH stabilization on TM)
  - Apply passive control schemes (tuning of L-mode and early H-mode profiles)

Overall plan for DT-1 (I)

FPO-1

- ~ 11 months: Commissioning 15 MA/5.3 T H, L-mode, 50 s →
- ~ 1 month: 15 MA/5.3T H+T, 50 s →
- ~ 4 months: 3.75 - 7.5 MA/2.65T D, H-mode 50 s

FPO-2 (**P_{fus} ≥ 100MW**)

- ~2 months: Commissioning H&CD t_{HCD} ≥ 600 s
- ~0.7 month: 5.0-7.5 MA/5.3T D, 50 s →
- ~2.5 months: 7.5 MA/5.3T DT, 50 s →
- ~2.5 months: 10 MA/5.3 T D, 50 s →
- ~ 8.3 months: 10 MA/5.3T DT, 50s

FPO-3 (**P_{fus} = 500MW**)

- ~2 months: Commissioning H&CD t_{HCD} ≥ 600 s →
- ~2.5-5 months: I_{p1} – I_{p2}/5.3T D, 50 s →
- ~ 8.5 months: I_{p2}/5.3T DT, 50s
  - **Q ≥ 10 P_{fusion} = 500 MW t_{burn} = 50 s**
  - **First attempt to Q = 10 t_{burn} > 50 s**

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Overall plan for DT-1 (II)

FPO-4
(P_{fus} = 500MW)

~2 months — Commissioning H&CD t_{HCD} ≥ 600 s

~3 months — I_{p2}/5.3T D, 300s, 1st scheme (active)

~ 1.5 months — I_{p2}/5.3T DT, 300s, 1st scheme (active)

~3 months — I_{p2}/5.3T D, 300s, 2nd scheme (passive)

~ 1.5 months — I_{p2}/5.3T DT, 300s, 2nd scheme (passive)

~3 months — I_{p2}/5.3T D, 300s, 3rd scheme (passive)

~ 1.5 months — I_{p2}/5.3T DT, 300s, 3rd scheme (passive)

- **First Q ≥ 10 P_{fusion} = 500 MW t_{burn} ≥ 300s**

FPO-5
(P_{fus} = 500MW)

~2 months — Commissioning H&CD t_{HCD} ≥ 1000 s

~ 1 month — I_{p2}/5.3T DT, 300s, Q ≥ 10 reproducible operation

~ 2 months — I_{px}/5.3T D, 300s, high duty operation

~ few days — I_{px}/5.3T DT, 300s, P_{fusion} = 250 MW, high duty

~ 1 month — I_{p2}/5.3T DT, Q ≥ 10 tburn = 300-500 s

~ 10 months — Time reserved to complete DT-1 objectives if difficulties arise

- **Reproducible Q ≥ 10 P_{fusion} = 500 MW t_{burn} ≥ 300s**
- **High duty operation with P_{fusion} = 250 MW**

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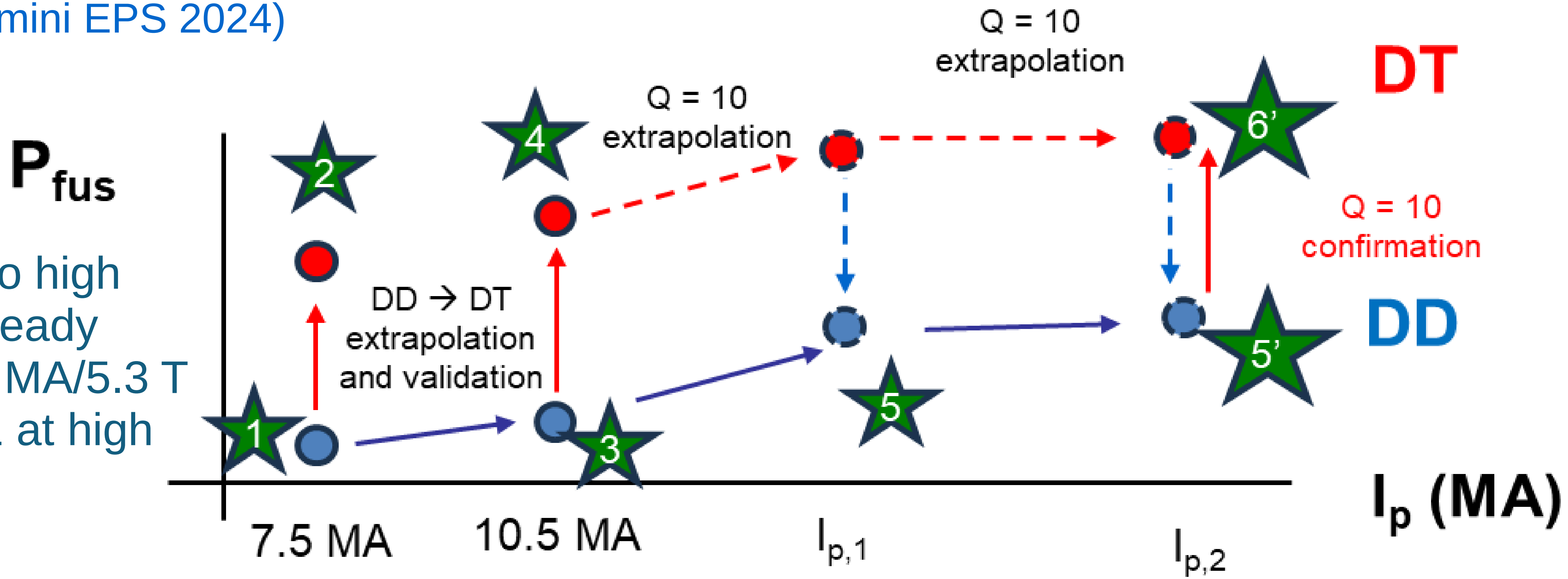
Strategy is to interleave DD and DT to minimize use of neutron fluence

- Develop 50-50 DT H-mode scenarios by D and D + T (< 50%) H-mode scenarios
- Validate plasma models at lower (I_p, %T) ←→ predict next step and repeat
  - Strategy used successfully in JET DTE-2 (J. Garcia NF 2023, C.F. Maggi NF 2024, F. Rimini EPS 2024)

- Access to high P_{fusion} already from 7.5 MA/5.3 T if H_{98} > 1 at high q_{95}



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