Introduction to the ITER project
(and its scenario development and plasma control)

Peter de Vries
ITER Organization
25 July 2022

ITER is a Nuclear Facility INB-174. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

The scope of this lecture

This lecture will not introduce the basics of plasma physics or tokamak operation or fusion physics, but assume a level of basic knowledge on these matters. The following points will be covered:

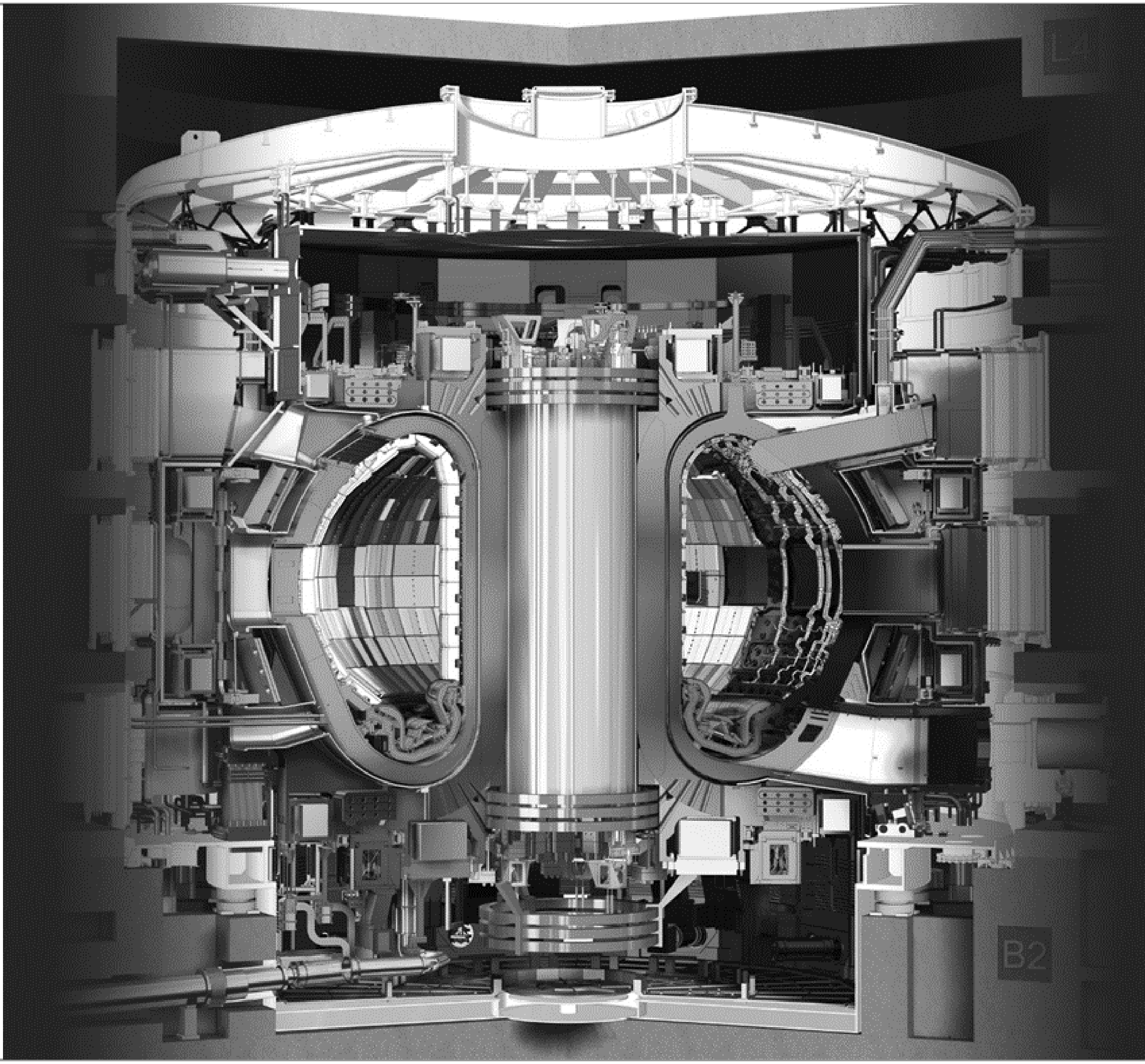
- ☐ What are the main goals and challenges of the ITER project?
- ☐ How will ITER be deployed and specifically what is the ITER Research Plan?
- ☐ What operation scenarios are relevant to ITER?
- ☐ What are the main challenges for the ITER Plasma Control System?
- ☐ How is the ITER Plasma Control System developed?
- ☐ What is the current status of the ITER project and device assembly

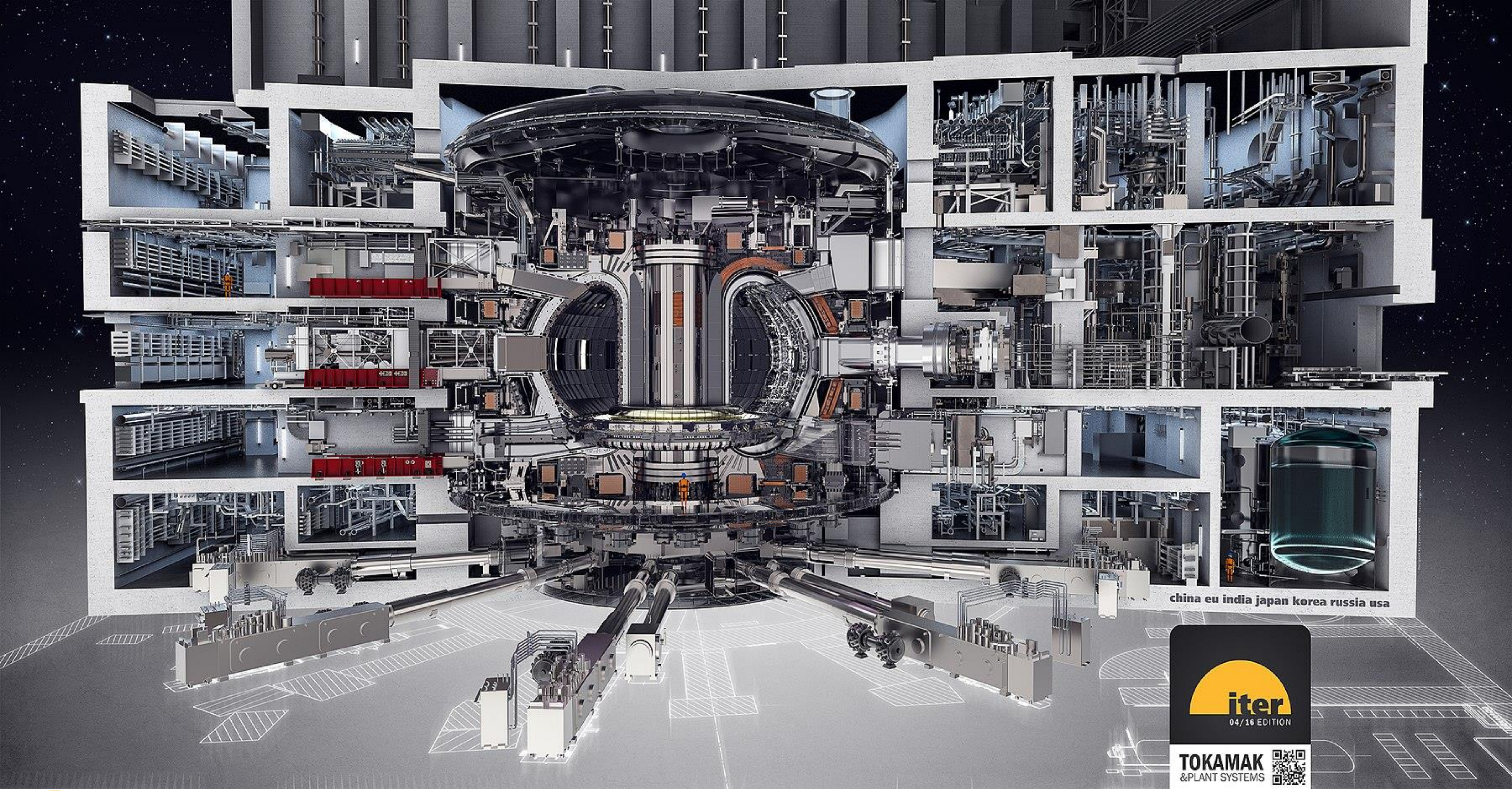
This lecture will introduce a number of aspects that will be discussed in more detail in several other lectures, as will be indicated on these slides.

What is ITER
and what does it aim to achieve?

What is ITER?

- ❑ ITER is a large **tokamak**, that 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 target of Q=10 at a plasma current of 15MA**, so called burning fusion plasmas.
  - Tokamak major radius: 6.2m
  - Toroidal field and current: 5.3T and 15MA
  - Combined stored magnetic energy: 15GJ
  - Plasma volume: >800m^3
  - Auxiliary heating power: 73MW
  - Fusion power: 500MW
  - Vacuum Vessel volume: 1000m^3
  - Device weight: 23000 Tonnes
  - Cryostat: 29m wide 29m high, 16000m^3
- ❑ ITER will maintain burning fusion plasmas for long periods of time. **And will test** the integrated technologies, materials, and physics regimes necessary for the commercial production of fusion-based electricity.




china eu india japan korea russia usa
iter
04/16 EDITION
TOKAMAK
&PLANT SYSTEMS

What is the ITER project?

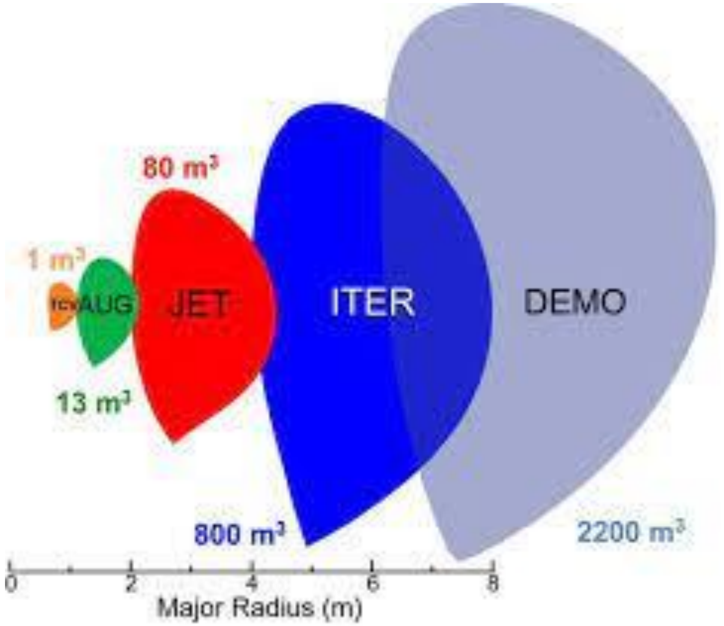
- ❑ Thousands of engineers and scientists have contributed to the design of ITER since the idea for an international joint experiment in fusion was first launched in 1985. The ITER Members: **China, the European Union, India, Japan, Korea, Russia and the United States**, are now engaged in a 35-year collaboration to build and operate the ITER experimental device, and together bring fusion to the point where a demonstration fusion reactor can be designed.

- ❑ The **ITER Organization** is an intergovernmental organization that formally established on 24 October 2007, aims to promote cooperation among the ITER members (Domestic Agencies DAs) that are involved in the development of ITER. It also acts as the **overall integrator of the project and nuclear operator of the ITER facility**.

What does ITER aim to achieve and what are some of the implications?

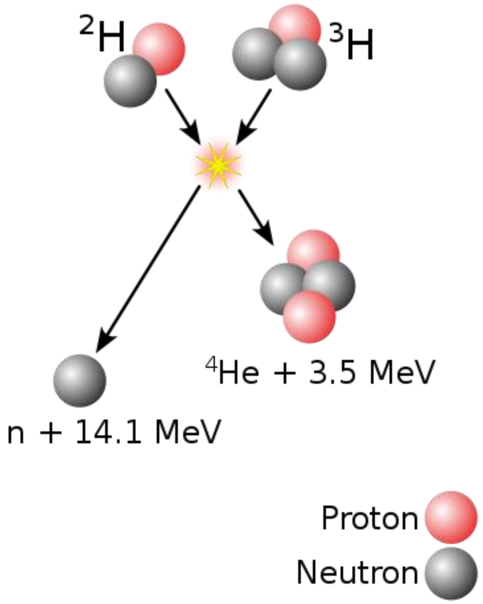
❑ Lets have a deeper look into the ITER aims and what the implications are: the **baseline ITER operation** is 15MA/5.3T, DT operation with a fusion gain of Q=10, generating 500MW of fusion power for 500s.

- Plasma can carry a large magnetic and thermal energy ➔ Tokamak discharge disruption loads
- Smaller surface to volume ratio, thus relatively small wetted area ➔ High heat loads on PFCs
- Operation at high, fusion relevant temperatures >20keV and at Q>5 ➔ New regime (burning plasmas)
- Very long term development and ongoing R&D ➔ Flexible design, allowing upgrades, component life-time



Operation at Q>5

- For DT fusion, Q=5 operation means that the plasma is heated equally by auxiliary means (i.e. NBI, ICH, ECH) and by the fusion generated α-power.



$$Q = \frac{P_{Fusion}}{P_{Auxiliary}} = \frac{P_{Neutrons} + P_{\alpha-particles}}{P_{Auxiliary}} \sim \frac{5 \cdot P_{\alpha-particles}}{P_{Auxiliary}}$$

$$Q > 5 \qquad\qquad P_{\alpha-particles} > P_{Auxiliary}$$

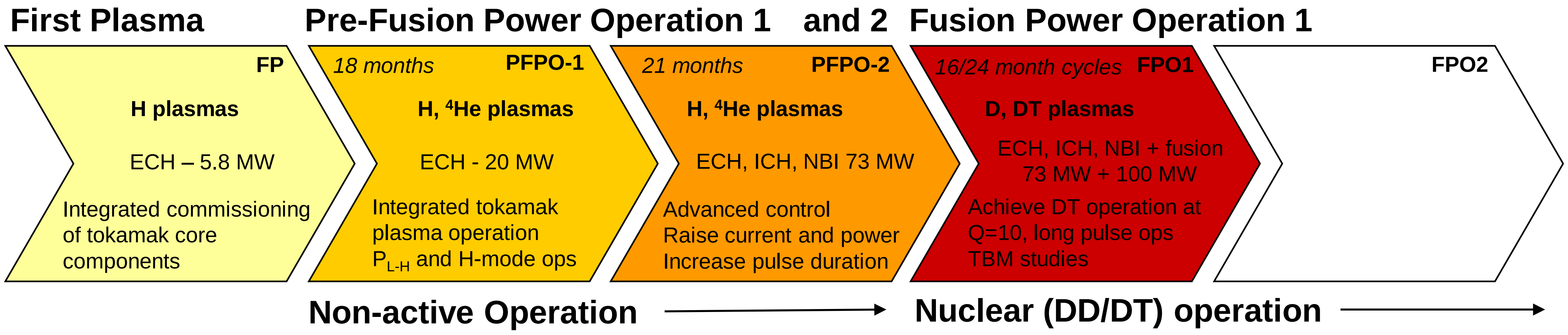
- ITER aims to operate at Q=10, thus a DT plasma dominantly heated by α-power, which obviously will have implications for how the tokamak discharge is controlled: ITER will have a relatively low auxiliary power (<0.1MW/m^3) and thus auxiliary heating power is not as effective an actuator as in today's tokamaks.

How is ITER deployed?
The ITER research plan

The ITER staged approach / ITER research plan

- The ITER the plant capabilities are progressively extended, adding new heating, fueling and diagnostic systems at each stage, **expanding the operation range of the device each time**, to reach the project target during at FPO (Fusion Power Operation)

- The ITER staged approach is aligned with the ITER research plan[1].



First Plasma **Pre-Fusion Power Operation 1 and 2** **Fusion Power Operation 1**

FP
H plasmas
ECH – 5.8 MW
Integrated commissioning of tokamak core components

18 months **PFPO-1**
H, ^{4}He plasmas
ECH - 20 MW
Integrated tokamak plasma operation
P_{L-H} and H-mode ops

21 months **PFPO-2**
H, ^{4}He plasmas
ECH, ICH, NBI 73 MW
Advanced control
Raise current and power
Increase pulse duration

16/24 month cycles **FPO1**
D, DT plasmas
ECH, ICH, NBI + fusion
73 MW + 100 MW
Achieve DT operation at Q=10, long pulse ops
TBM studies

FPO2

Non-active Operation →
Nuclear (DD/DT) operation →

---

[1] IRP is publicly available as ITER technical report ITR-18-003 https://www.iter.org/technical-reports

ITER Research Plan and Supporting R&D

- ❑ ITER Research Plan (IRP) informs fusion community on details of experimental plans (Level 3) to achieve project’s goals: ITER-18-003 at https://www.iter.org/technical-reports

ITER TECHNICAL REPORT

REPORT NO.
ITR-18-003

TITLE
ITER Research Plan within the Staged Approach (Level III – Provisional Version)

AUTHOR/AUTHORS
ITER Organisation

AUTHOR EMAIL(S)
ITR.support@iter.org

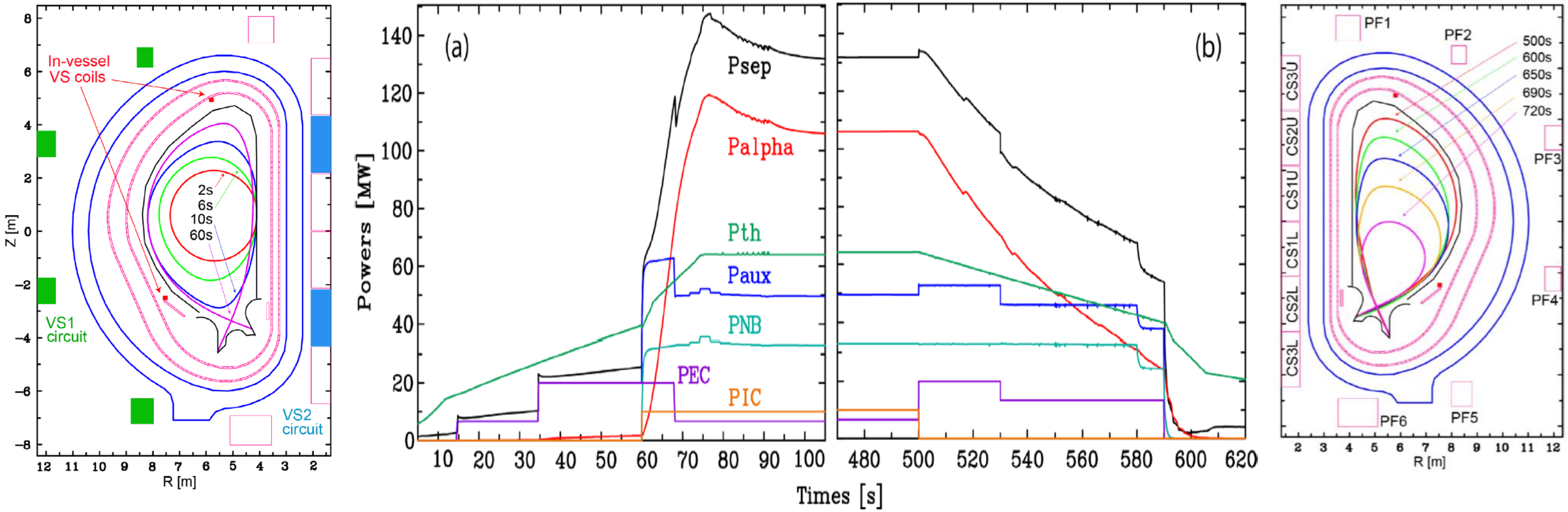
DATE
17th September 2018

www.iter.org

ITER operation scenarios as part of the ITER research plan

The ITER baseline scenario

- The **baseline scenario**: I_p=15MA/B_{TF}=5.3T q_{95}=3, P_{AUX}=50MW, controlled DT type I ELMy H-mode with P_{FUSION}=500MW and Q=10 is main goal to operate ITER.



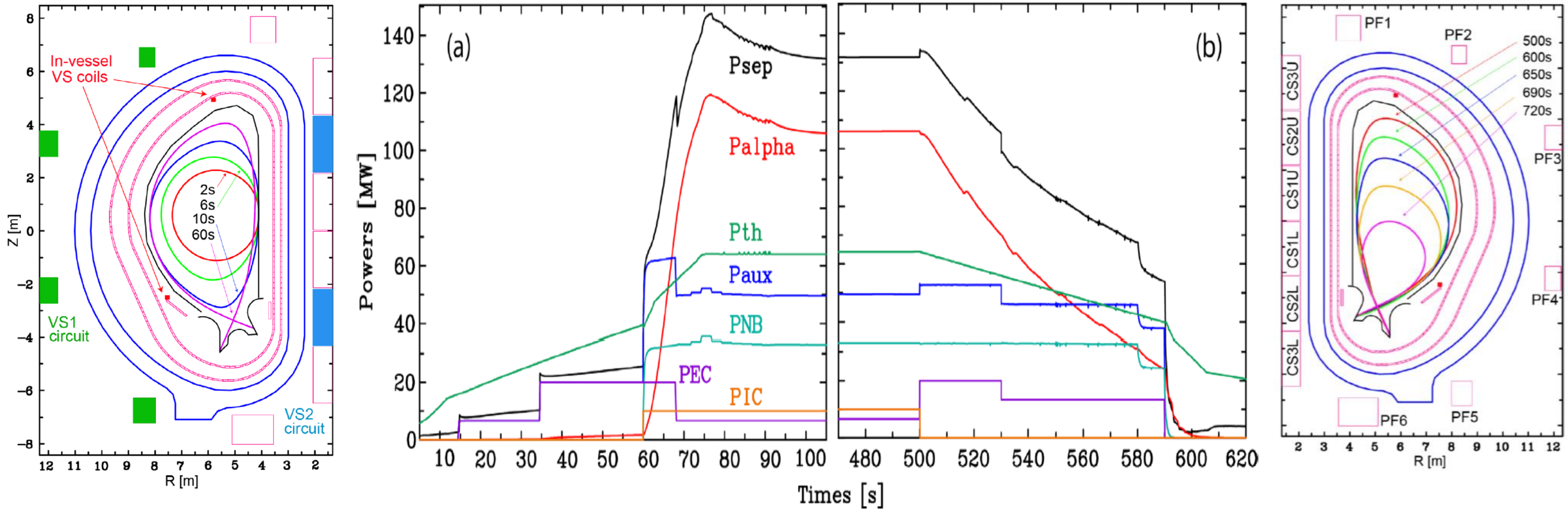
- It does not mean, ITER does not want or cannot operate differently. As long as these are technically feasible at ITER, other operation scenarios are possible.

S.H. Kim *et al., Nucl. Fusion* **58** (2018) 056013

➔ Lecture by F. Turco

The ITER baseline scenario

- The **baseline scenario**: I_p=15MA/B_{TF}=5.3T q_{95}=3, P_{AUX}=50MW, controlled DT type I ELMy H-mode with P_{FUSION}=500MW and Q=10 is main goal to operate ITER.



- It is important to realize that a baseline scenario choice is important **as it sets the basis for the ITER plant design**, and details of the design of the plasma facing components, the control systems, diagnostics, cooling water systems, magnets etc. **It also provides the current aim of the ITER research plan.**

S.H. Kim *et al., Nucl. Fusion* **58** (2018) 056013

➔ Lecture by F. Turco

Scenarios to facilitate the ITER Research Plan

- The IRP, starts with short, low current pulses, using only Hydrogen and/or Helium, aiming to validate design models and testing the basic tokamak control and disruption avoidance and mitigations strategies, aiming in PFPO-1 already for first ELMy H-mode operation.

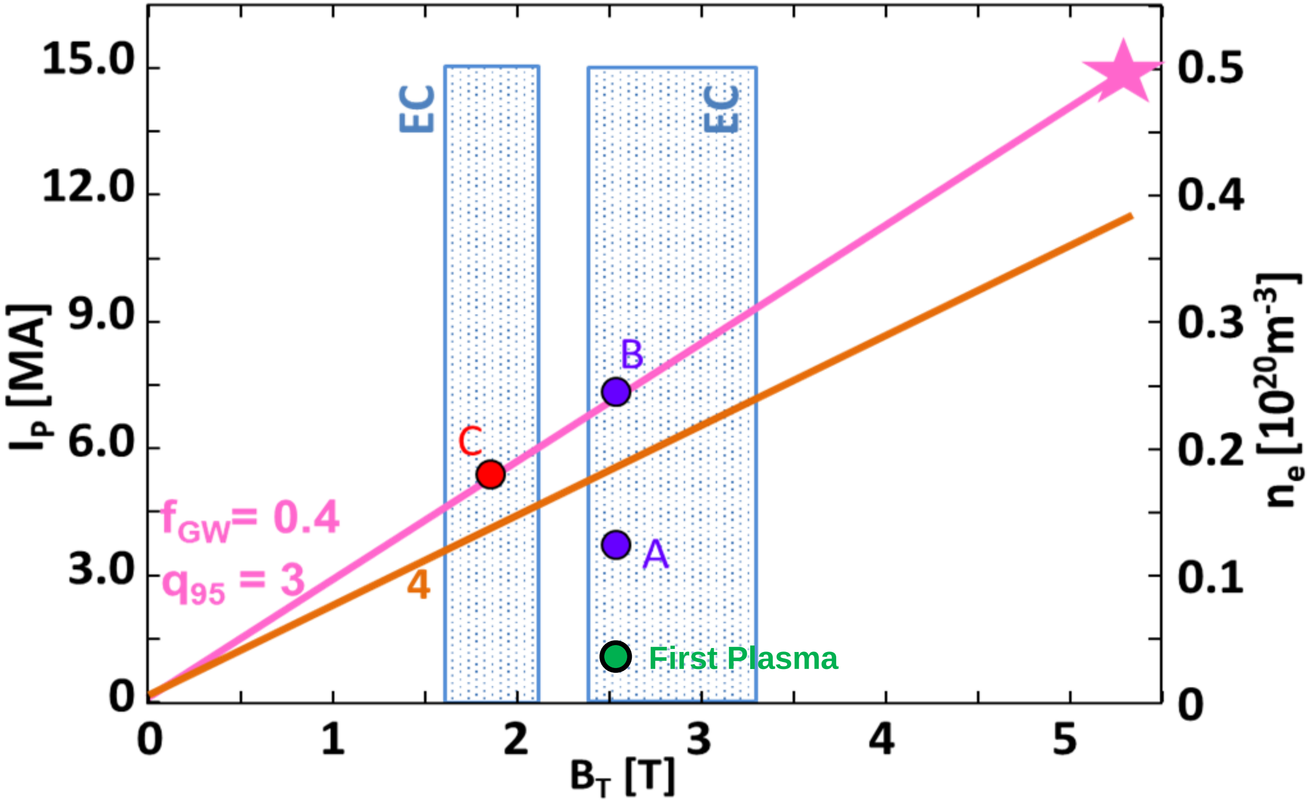
- Operation at lower current and/or plasma energy is less risky (e.g. small heat or disruption loads), however such scenarios may not necessarily be easy to operate, posing their own technical or scientific issues.

➔ Lecture by S.H. Kim

Scenarios to facilitate the ITER Research Plan

- ☐ The IRP, starts with short, low current pulses, using only Hydrogen and/or Helium, aiming to validate design models and testing the basic tokamak control and disruption avoidance and mitigation strategies, aiming in PFPO-1 already for first ELMy H-mode operation.

PFPO-1 L and H-mode

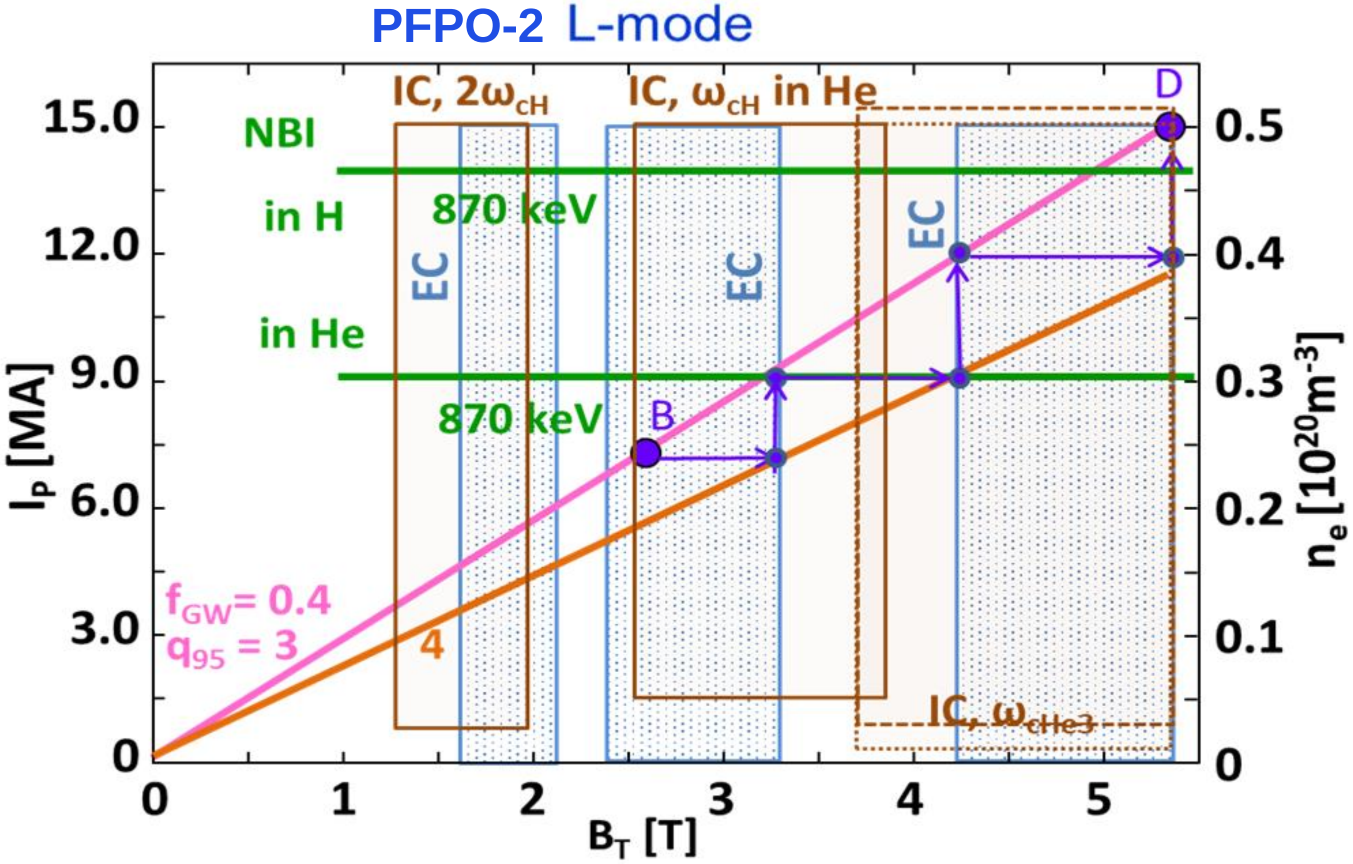


- **A.** 1st divertor plasma
  3.2 MA / 2.65 T
- **B.** q_{95}=3 plasma
  7.5 MA / 2.65 T
  - L-mode in PFPO-I
- **C.** 1st high confinement
  5 MA / 1.8 T

➔ Lecture by S.H. Kim

Scenarios to facilitate the ITER Research Plan

- ☐ During PFPO-2 more auxiliary power (from all three ITER heating systems: EC, IC and NB) is available to progressively expand the ITER operation space, to 15MA in L-mode.
  - The choice of the scenario operation points is dictated by the specifics of the various heating schemes



- **B.** q_{95}=3 plasma
  7.5 MA / 2.65 T
  - L-mode

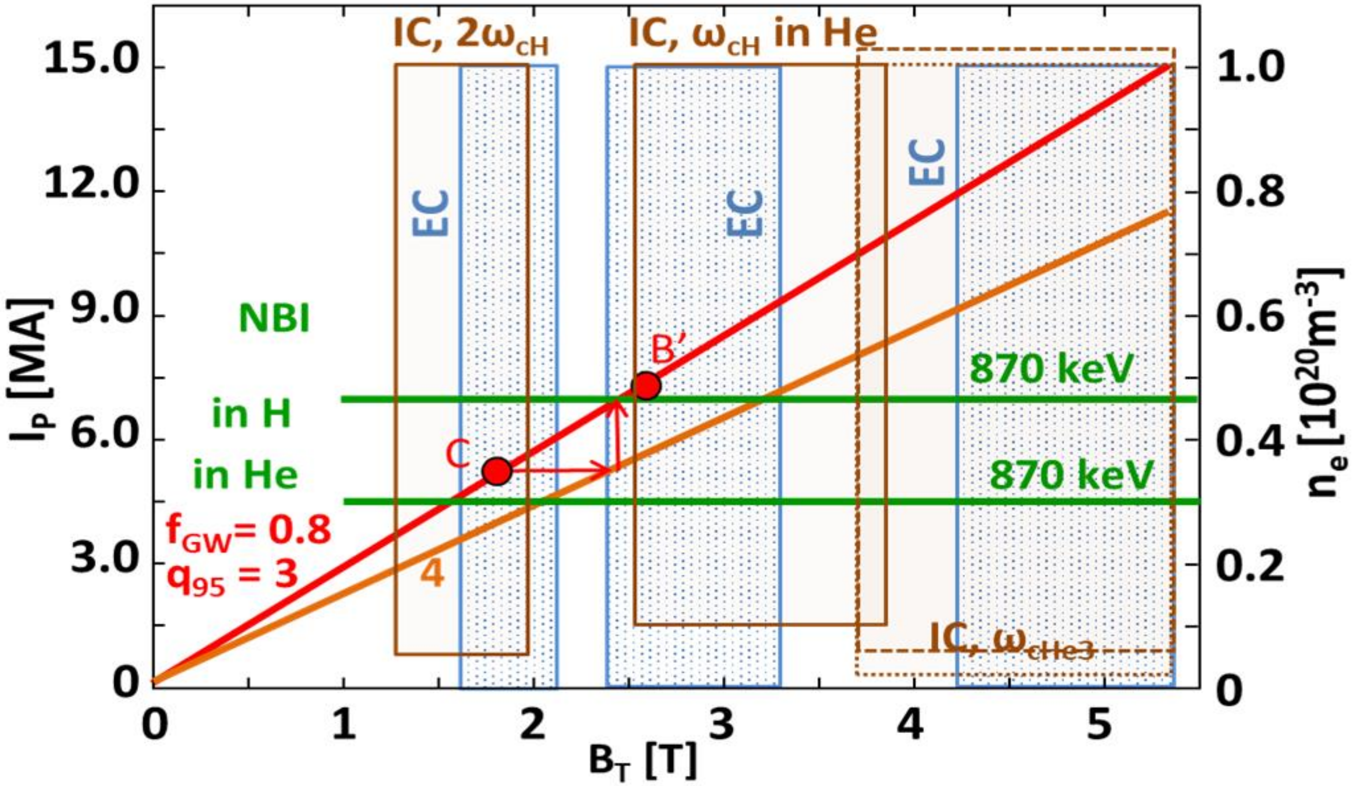
- **D.** *q_{95}=3 plasma*
  15 MA / 5.3 T
  - *L-mode*

➔ Lecture by S.H. Kim

Scenarios to facilitate the ITER Research Plan

- During PFPO-2 ELMy H-mode operation in Hydrogen and Helium will be further developed, and advance control techniques, such as ELM, NTM and detachment control as well as disruption avoidance will be established to prepare for **ITER baseline operation in FPO**.

PFPO-2 H-mode



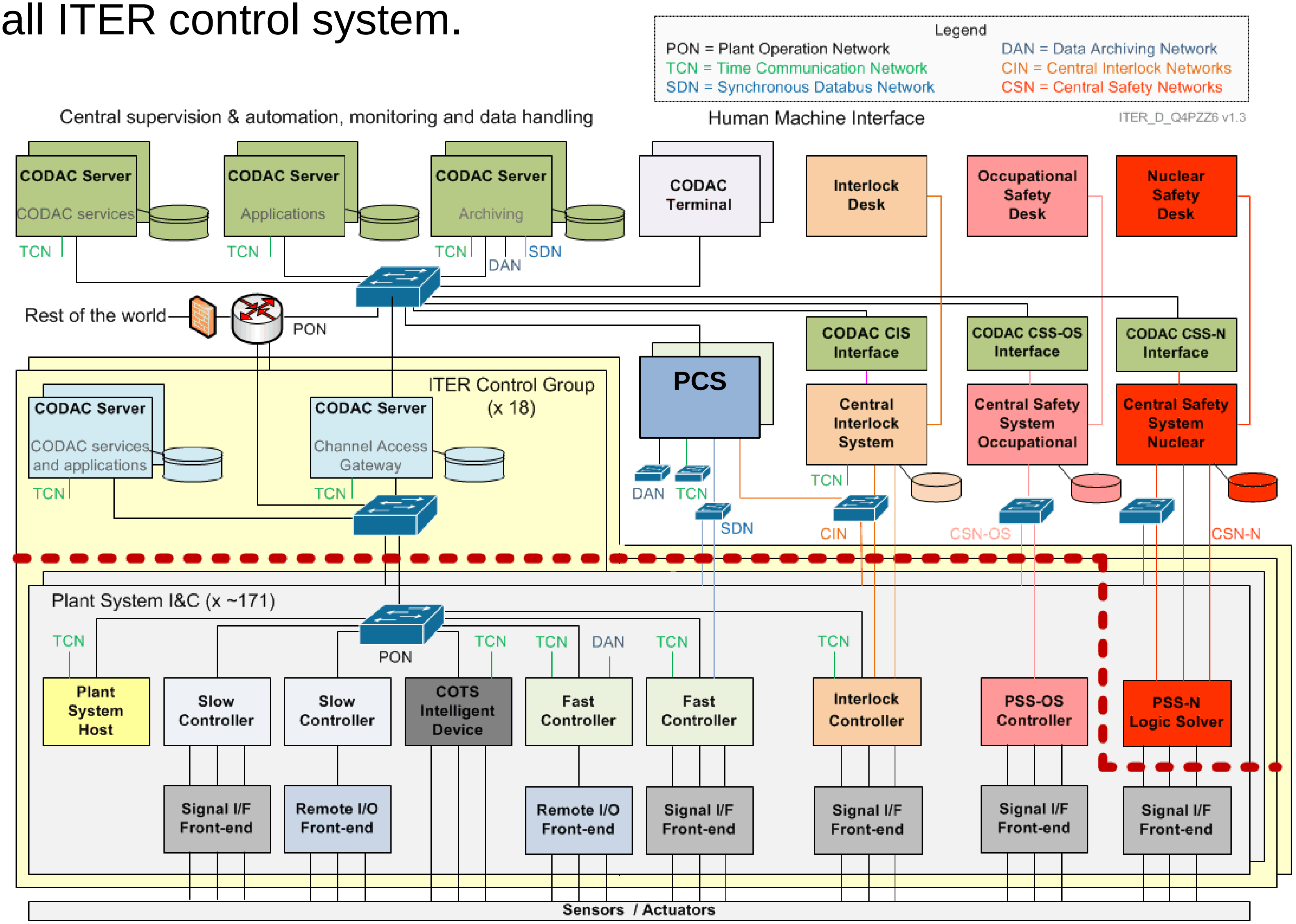
- *C. q_{95}=3 plasma*
  5 MA / 1.8 T
  - *H-mode*
- **B'.** q_{95}=3 plasma
  7.5 MA / 2.65 T
  - H-mode

➔ Lecture by S.H. Kim

The development of the ITER Plasma Control System

What is the ITER Plasma Control System?

- The ITER PCS one part of the overall ITER control system.

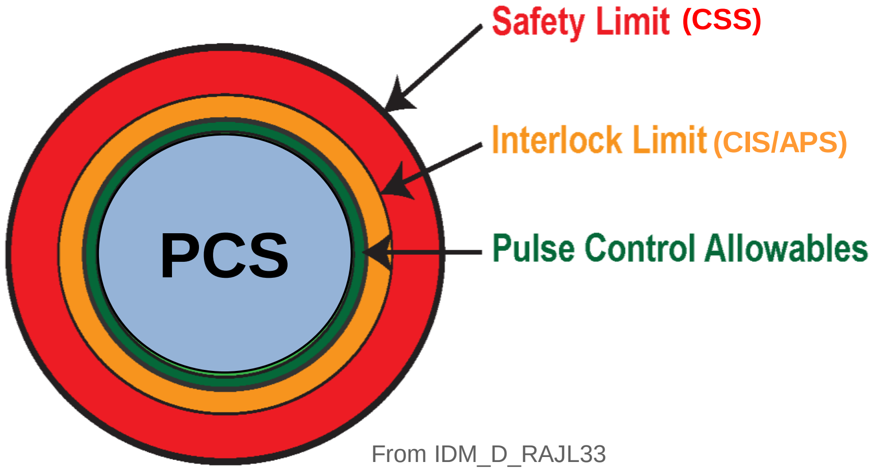


From IDM_D_RAJL33

What is the ITER PCS and what is it not?

- ❑ Tokamak operation is done in pulses. During an ITER pulse the Plasma Control System (PCS) provides fully autonomous and integrated control of those systems needed to facilitate the pulse scenario, deploying both continuous control and asynchronous control (e.g. exception handling).

- ❑ During a pulse, the PCS will aim to avoid operation limits, but the ITER PCS is not responsible for device protection. The ITER defense-in-depth strategy provides machine protection and safety, **independent** from the nominal Tokamak control, e.g. the PCS.



From IDM_D_RAJL33

- ❑ The PCS is at the heart of Tokamak control and fully integrated with the operation of ITER.

Plasma Control System (PCS)

- ❑ It is not the aim to go into the detail of various control schemes or methods that ITER requires, because many of these will be addressed by the other lectures at this school. Just to recap, the ITER PCS will have to perform:
  - Magnetic control: e.g. controlling the magnets and the magnetic configuration.
  - Kinetic control: e.g. gas dosing, fueling with gas and pellets, density control but burn control.
  - Instability control: e.g. VS, EF, NTMs, ELM, RWM or TAE control.
  - Disruption avoidance and mitigation schemes.
  - First wall heat load control: e.g. detachment control, ELM control.
  - Control for RF wall cleaning methods.

- ❑ ITER will be the first Tokamak that **requires the integration** of all of the above control schemes into its PCS often to be deployed simultaneously.

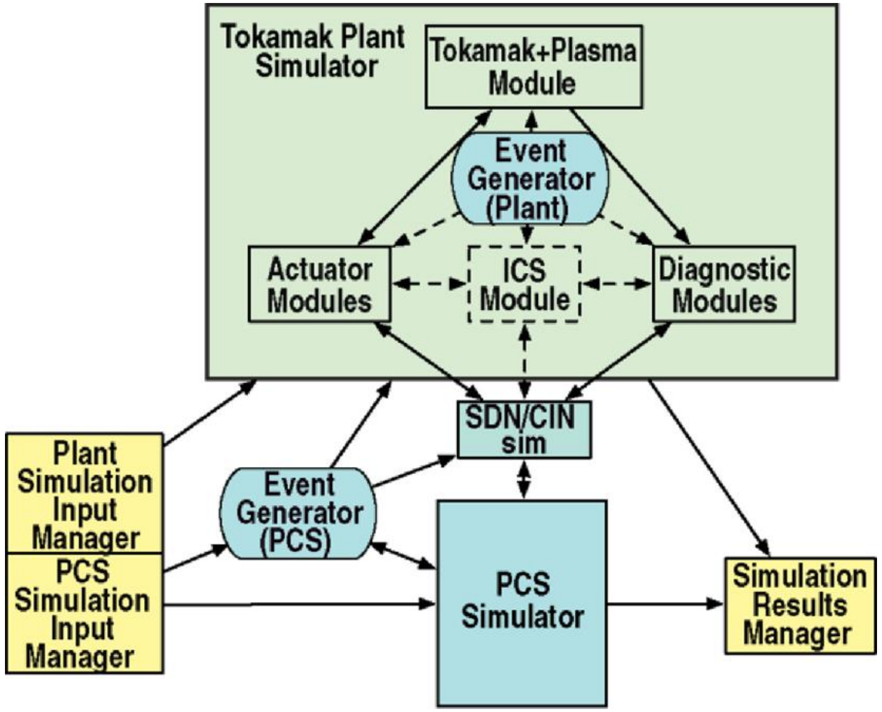
- ❑ Here the main challenges to the design and deployment the ITER PCS will be discussed, and the strategies to overcome them.
  - The long time-scales involved with the development of the system.
  - The relationship between control design and scenario development.
  - Understand exactly what control and how it is needed.
  - Managing the design integration.

➔ Introduction by M. Walker
➔ Lecture by G. de Tommasi
➔ Lecture by D. Humphreys
➔ Lecture by D. Eldon
➔ Lecture by E. Schuster

The long time development of the system

- ❑ To show that the controller design works, in the future, it requires full simulation of the control loop, thus also the **capability to simulate** the sensor, actuator together with the plant response
  - Actuators or diagnostics differ per device ➔ Control design choices are often made incorporating these differences
  - What sensor signals will be available for ITER control?

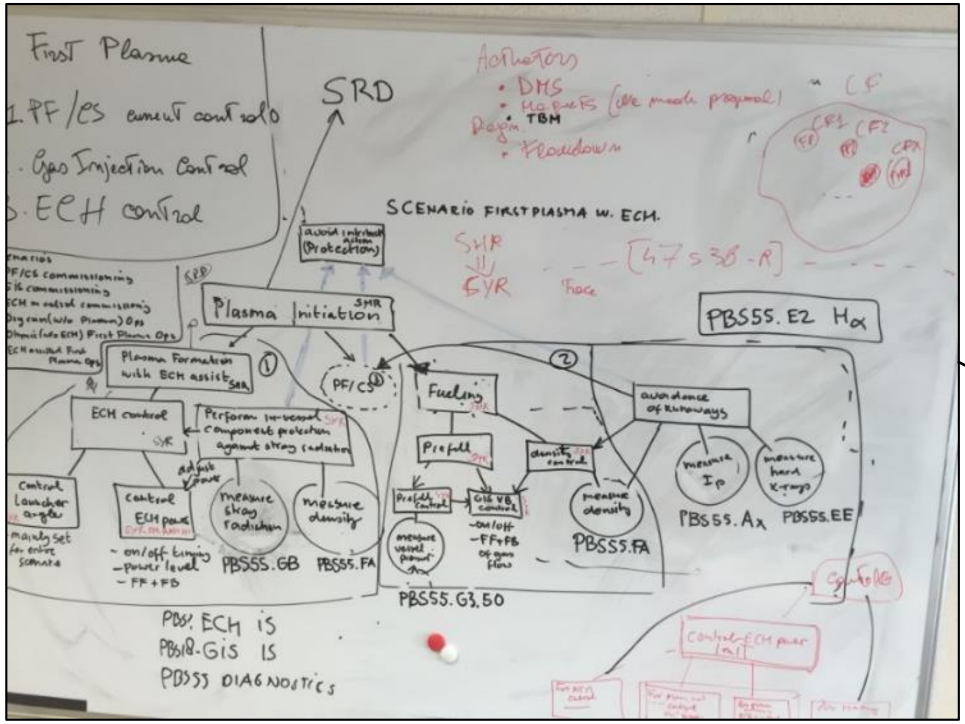
- ❑ **The capability of simulate and assess control functionality** and thus **availability of validated models** (for sensors, actuators, plasma response) are therefore essential.
  - The ITER PCS design uses the Matlab/Simulink © based **PCS Simulation Platform**[1,2].

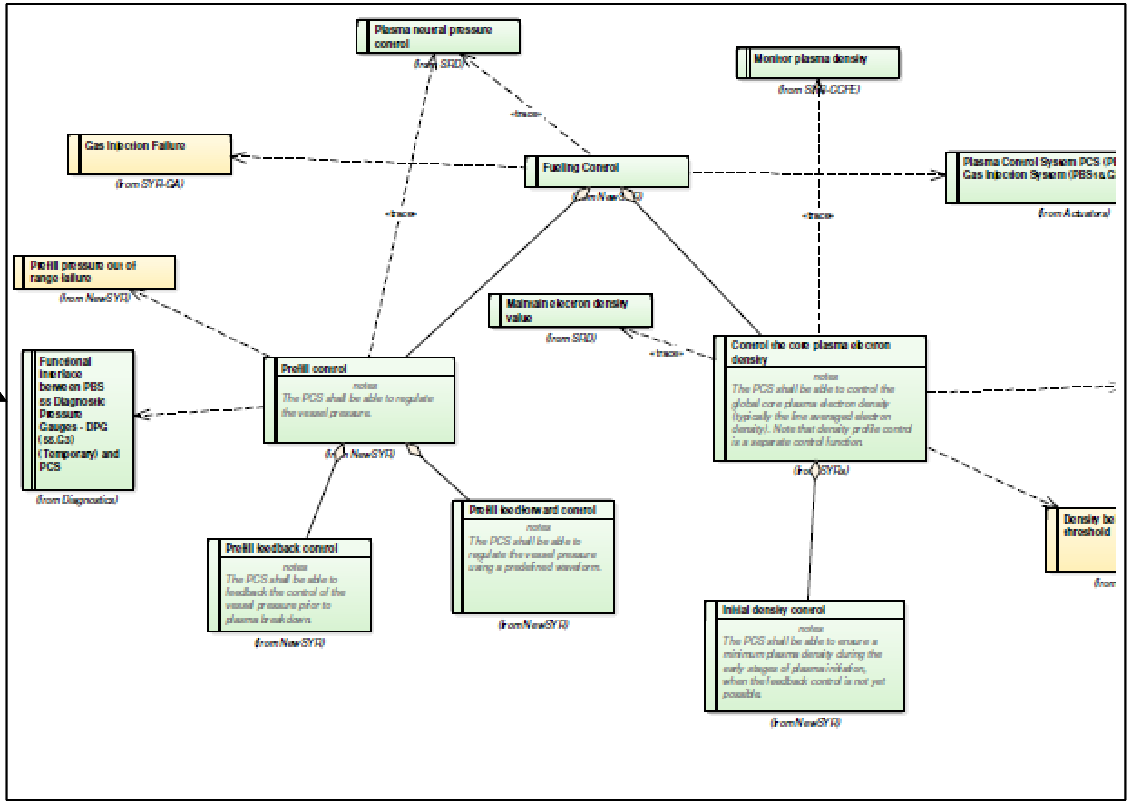


[1] M.L. Walker, et al., Fus. Eng. Des. 96-97 (2015) 716.
[2] M.L. Walker, et al., Fus. Eng. Des 146B (2019) 1853

The long time development of the system

- ❑ It also requires a systematic approach to the design and deployment:
  - The ITER PCS design and deployment follows the ITER staged approach ➔ It is designed in steps for each stage.
  - It applies a **System Engineering** approach[1] providing a consistent and clear design description, with traceability between requirements, PCS design, PCS simulations in PCSSP and eventually its RT implementation





[1] M. Cinque, et al., Fus. Eng. Des **146** (2019) 447.

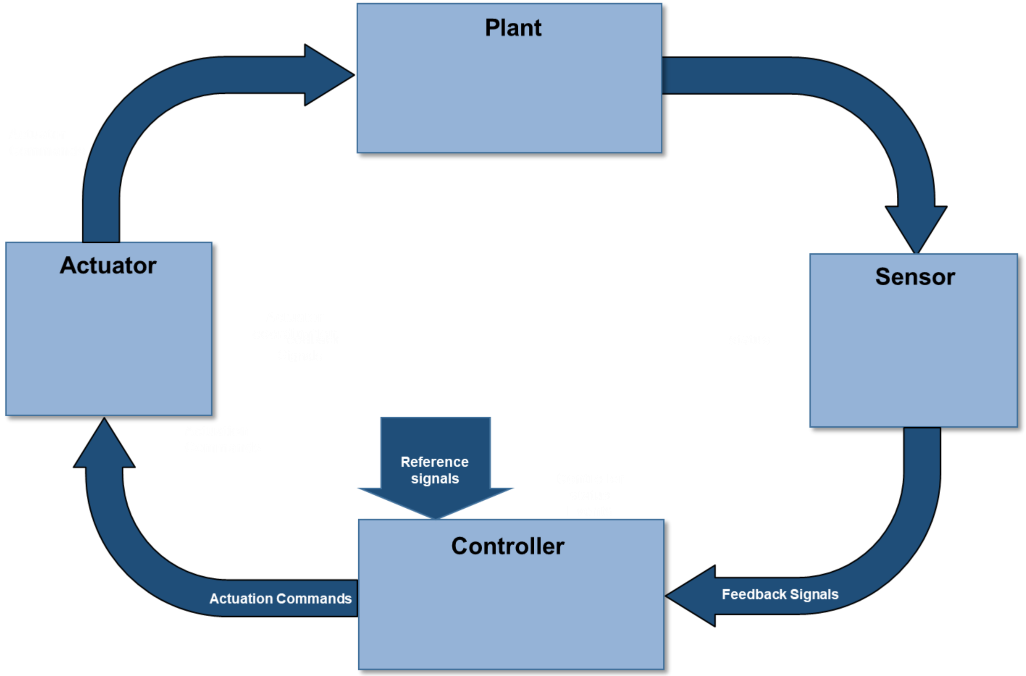
Control design and scenario development

- ❑ The PCS design uses simulated scenarios as input (i.e. it is designed to achieve a certain operation scenario), but these operation scenarios may have to be designed with control functionality in mind.
- ❑ There is synergy between simulations for operation scenario design and simulations that assess the functionality of the PCS.
- ❑ However these two things are not the same, with the latter often focusing on “closing the loop” and having to take into account details on sensor and actuators functionality, while scenario design focuses on plant/plasma response models and operation limits.

➔ Lecture by H. Zohm
➔ Lecture by M. Walker
➔ Lecture by W. Treutterer
➔ Lecture by F. Poli
➔ Lecture by I. Bandyopadhyay

Understand exactly what control is needed

- ☐ To design the ITER PCS we should have a clear understanding what it is what it should do?
  - What are the ITER operation scenarios for each stage? ➔ What do we want to achieve, with what tools?
  - Do we really understand what control functions need to achieve? ➔ control what? And how (e.g. FB, FF, EH)?
  - And how accurate should the control be? ➔ what are the performance requirements?
  - To what extend is ITER operation needed to further optimize the control? ➔ Use operational time to improve control.



What do we need to know for the PCS design?

- Its functions and what needs to be controlled? → System Requirements + IRP
- How and under what conditions should it function? → **Physics operation scenarios** + IRP

- How well should it be controlled? → Performance requirements
- **What are actuator characteristics?** → Functional interface sheets
- What are the diagnostic characteristics? → Functional interface sheets
- What data is exchanged in real-time? → Data exchange interface sheets
- What are the operation limits? → Plasma physics + system interface sheets

- What are the sensor or diagnostic model(s) → **Synthetic diagnostics**
- What are the actuator responses → Actuator response models
- What is the plant and/or plasma response → Plasma/plant response models

How to manage functional relationships?

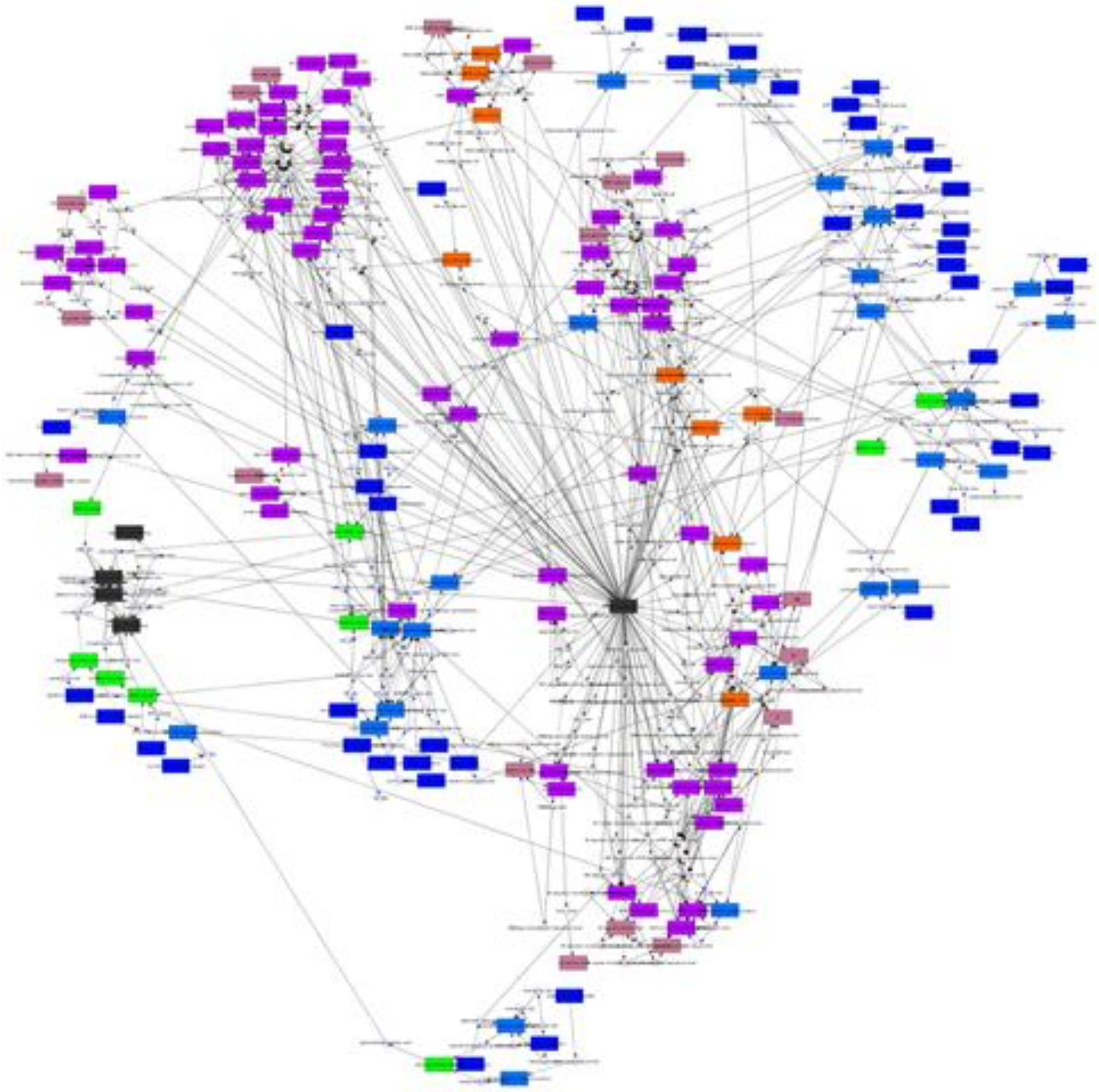
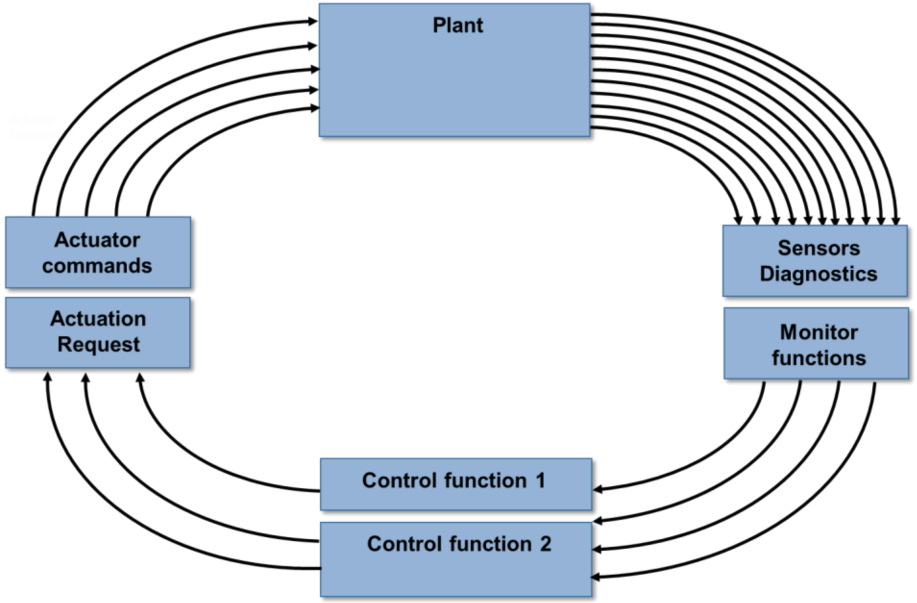


Figure by W. Treutterer

Managing the control integration

- ❑ Design integration
  - How do we simulate that the design integration is correct? ➔ how do the various controllers work together and interact?
  - What strategy do we employ to assess that our exception handling design? ➔ We have to make choices.
  - It is easy to underestimate the extend of the design of exception handling in PCS.

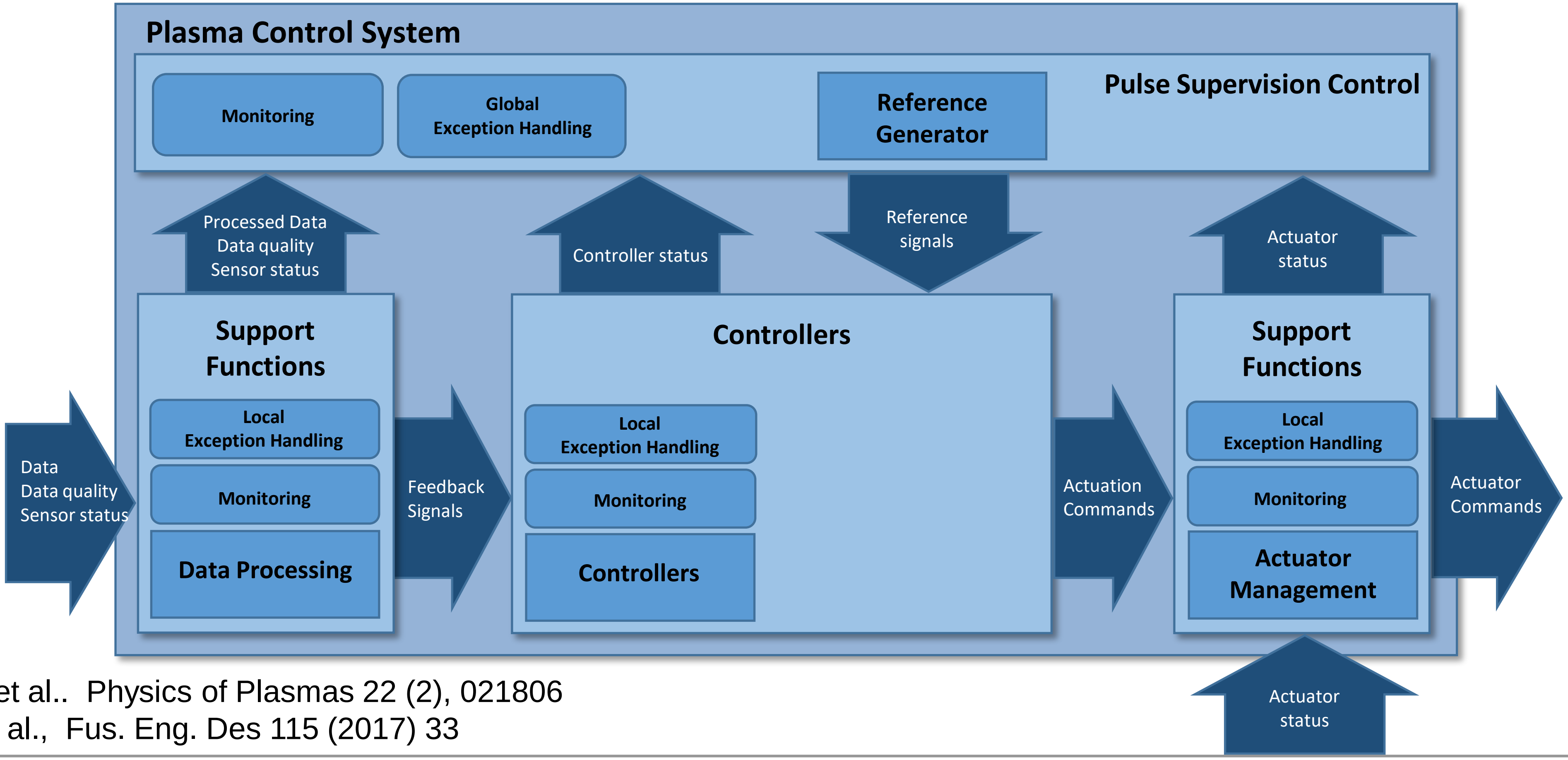
- ❑ Control integration can be managed by:
  - A systematic design method.
  - Ensuring standardization and a solid control architecture.
  - Develop clever actuator management or monitor support functions.
  - A good strategy to assess coupling between various control functions.



➔ Lecture by F. Felici

Basic sketch of the ITER PCS architecture

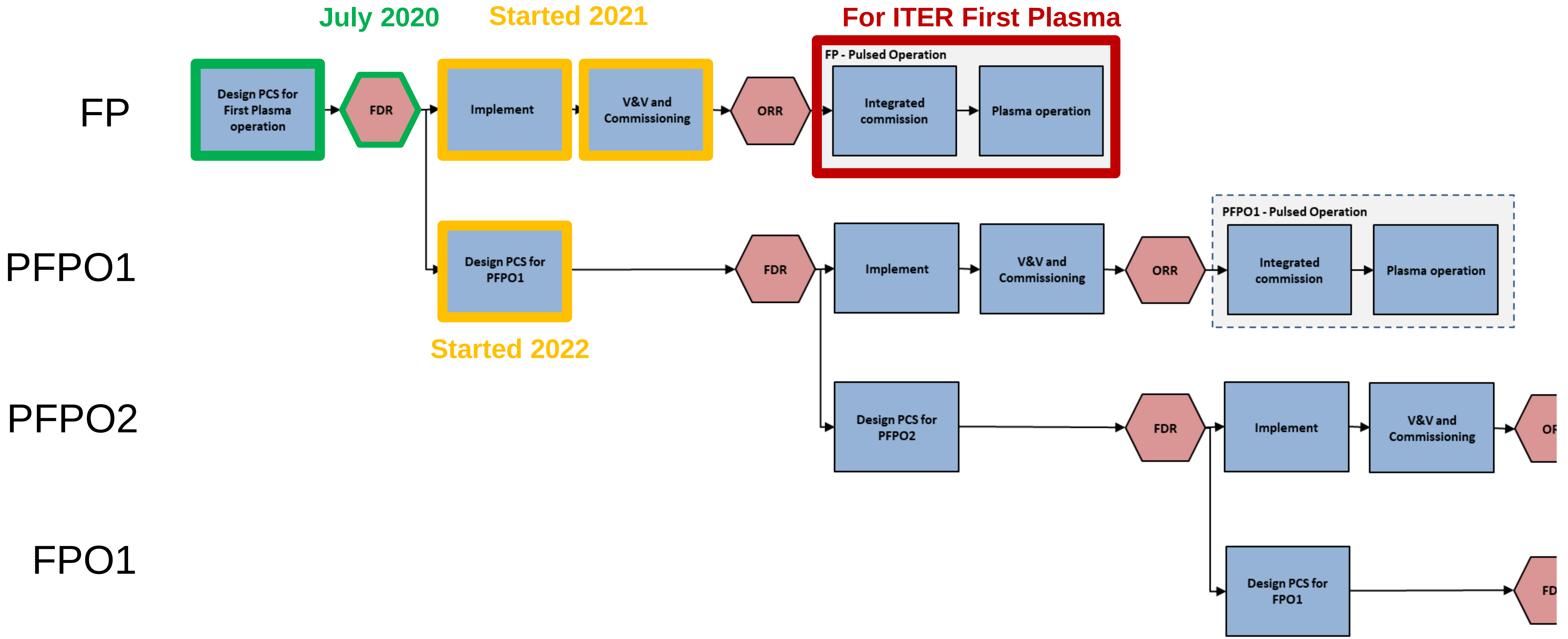
- A PCS supervisor manages integration, scheduling the pulse, for example by generating the control request waveforms and managing global exception handling.
  - A multitude of support functions, process data, monitor limits, convert actuation commands or manage the allocation of actuator commands.



[1] D. Humphreys, et al.. Physics of Plasmas 22 (2), 021806
[2] W. Treutterer, et al., Fus. Eng. Des 115 (2017) 33

The PCS design and development schedule

- ❑ PCS functions are designed, reviewed (FDR), implemented and commissioned **prior to the start of each operation stage**. PCS integrated commissioning takes place during the operation stage, either with or without plasma pulses.



The current status of the ITER Project
The ongoing Tokamak assembly

Progress in major areas (as of December 2021)

🟩 **F4E completed construction works**
Buildings handed over to IO

Ongoing construction works

🟨 **Tokamak Complex**
(Nuclear Buildings)
B11 – Tokamak Building
B14 – Tritium Building
B74 – Diagnostics Building

🟦 **B15 – RF Heating Building**
B51, B52 – Cryoplant Buildings
B37 – NB High Voltage Power Supply Building
B71-N – Control Building North
B75 – FD & Switching Network Resistor Building

Site infrastructure ongoing across platform

The construction of the ITER Main Control Room (MCR)

The construction of the ITER Main Control Room (MCR)

Main Control Room design

Design of Main Control Room performed under contract, but based on interviews with a representative cross-section of ITER Organization staff and a number of workshops

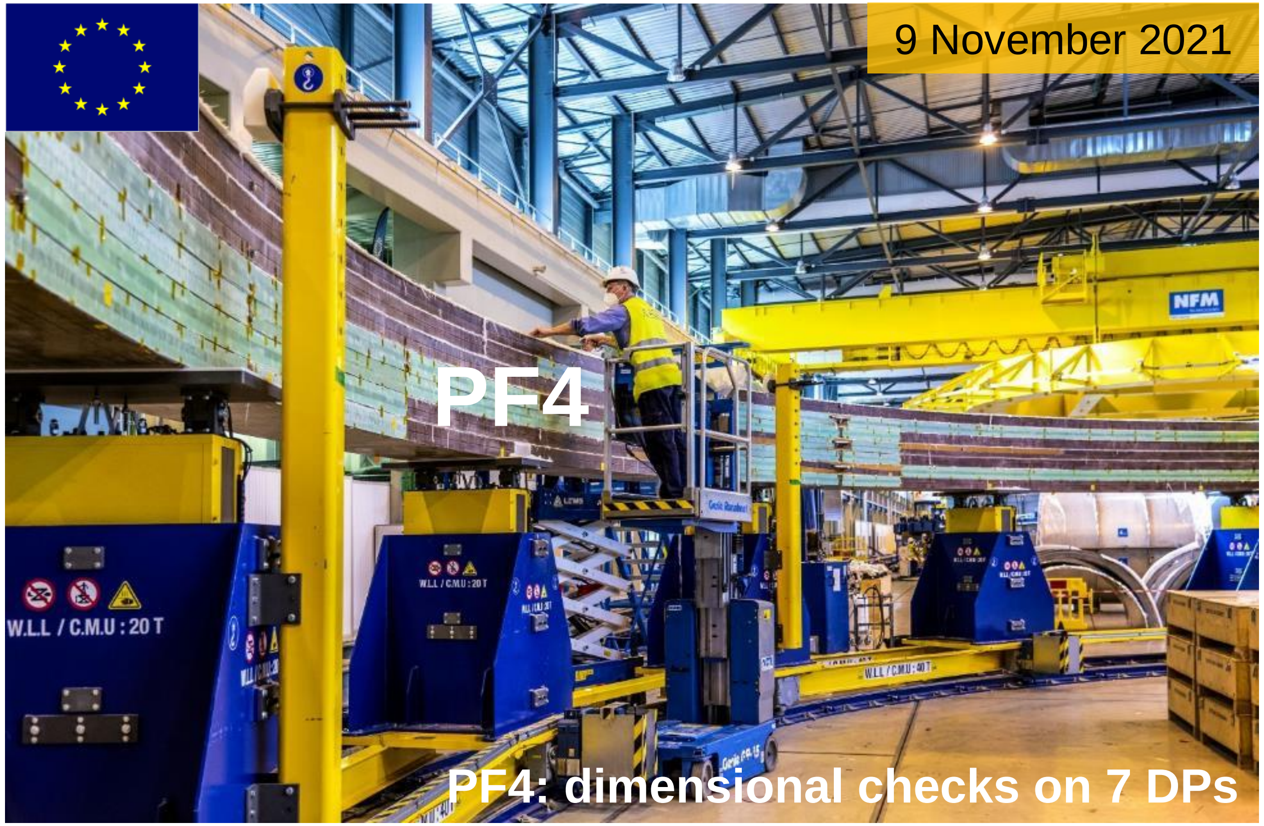
Construction of the NBI Building

16 February 2022

Progress on Poloidal Field coil manufacturing

PF6, PF5: complete and assembled
PF2: Complete and in storage
PF4: All Double Pancakes (DPs) impregnated
PF3: 2nd DP winding ongoing

PF1: Clamps, closing plates, cryogenic strapping and diagnostic systems installed.
Delivery by RF to IO expected in 2022



9 November 2021

PF4: dimensional checks on 7 DPs

Toroidal Field coil progress

JA: 9 coils

3 coils delivered to IO and 2 more on the way to IO

2 coils in Winding Pack (WP) integration, 2 coils WP impregnation

EU: 10 coils

6 coils delivered to IO

3 coils in final stages

1 coild doing WP cold test

TF2: on the way to IO

TF4 being off-boarded at Fos-sur-Mer

Vacuum Vessel progress (March 2022)

KO:

Sectors 6, 7, 8 delivered to IO.

Sector 1 in final stage of manufacture

EU:

Sector 5: 97%. Sector 4: 93%

Sector 9: 86%, Sector 3: 81%,

Sector 2: 79%


14 January 2022

Sector 8 being loaded onto its transport

Sector 5 after inner shell welding

Cryostat

Pit assembly completed for the Cryostat Base Section and Lower Cylinder. Upper cylinder completed and in storage, assembly of Top Lid complete and preparing for storage

Cryo-plant commissioning

In the last 3.5 years, over 5000 tonnes of equipment has been installed and now a 2 year period of commissioning has started (with filling the plant with liquid Nitrogen in June 2022)

Cooling Water Plant

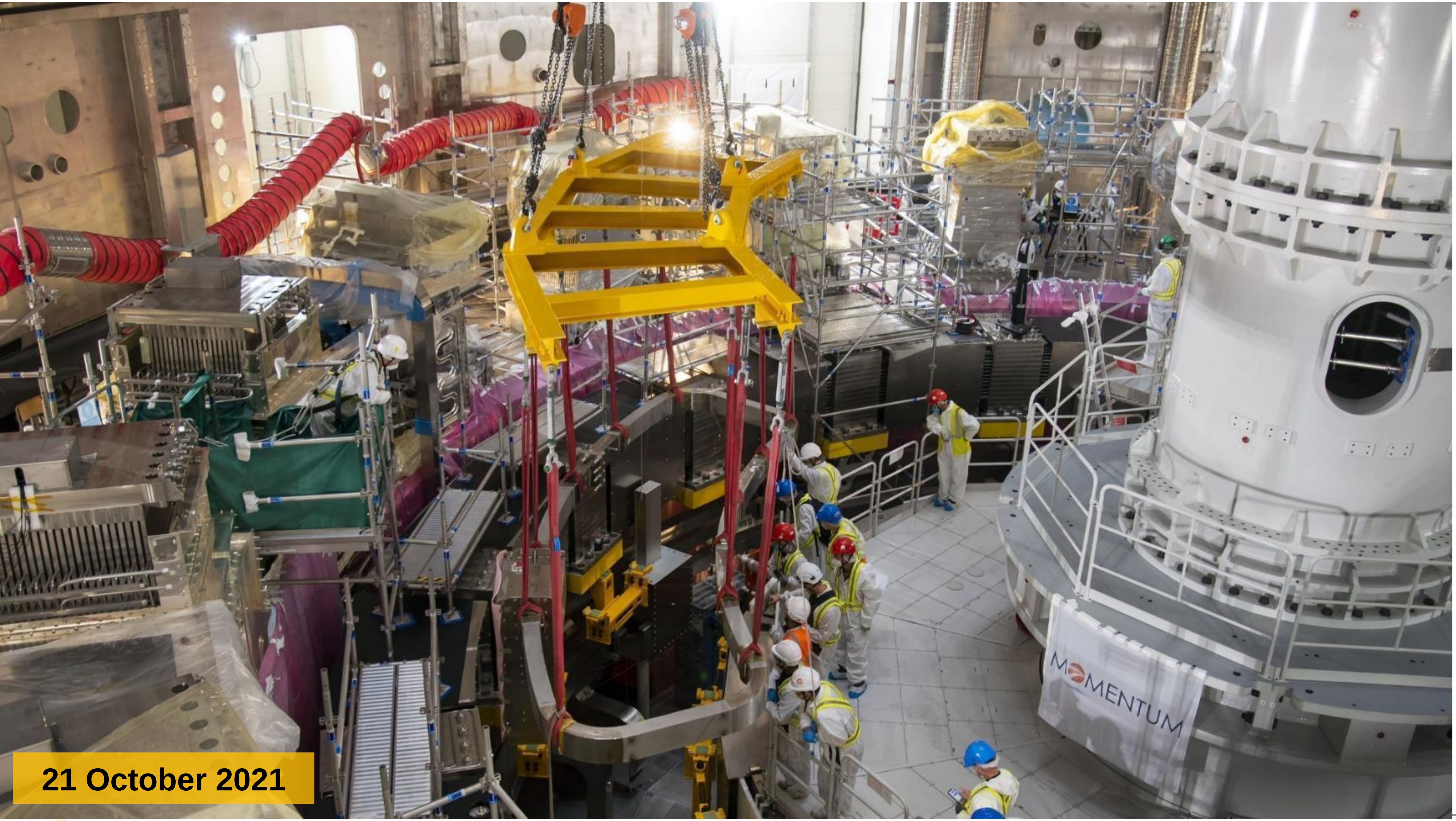

15 October 2021

About 6000 tonnes of equipment supplied by India. The cooling water plant commissioning has now started

Metrology and adjustment

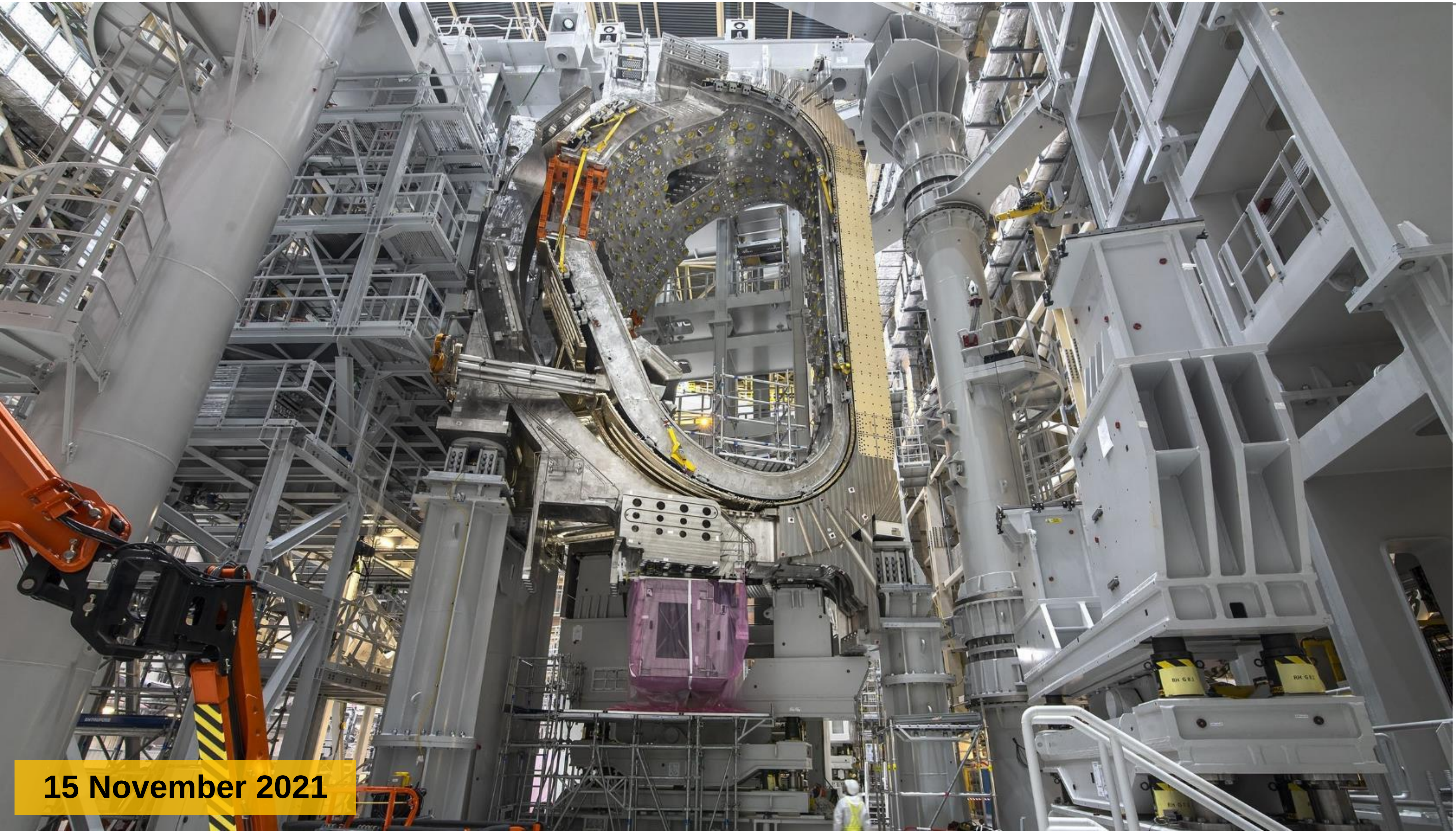
8 December 2021

Installation of bottom Error Field Correction Coils



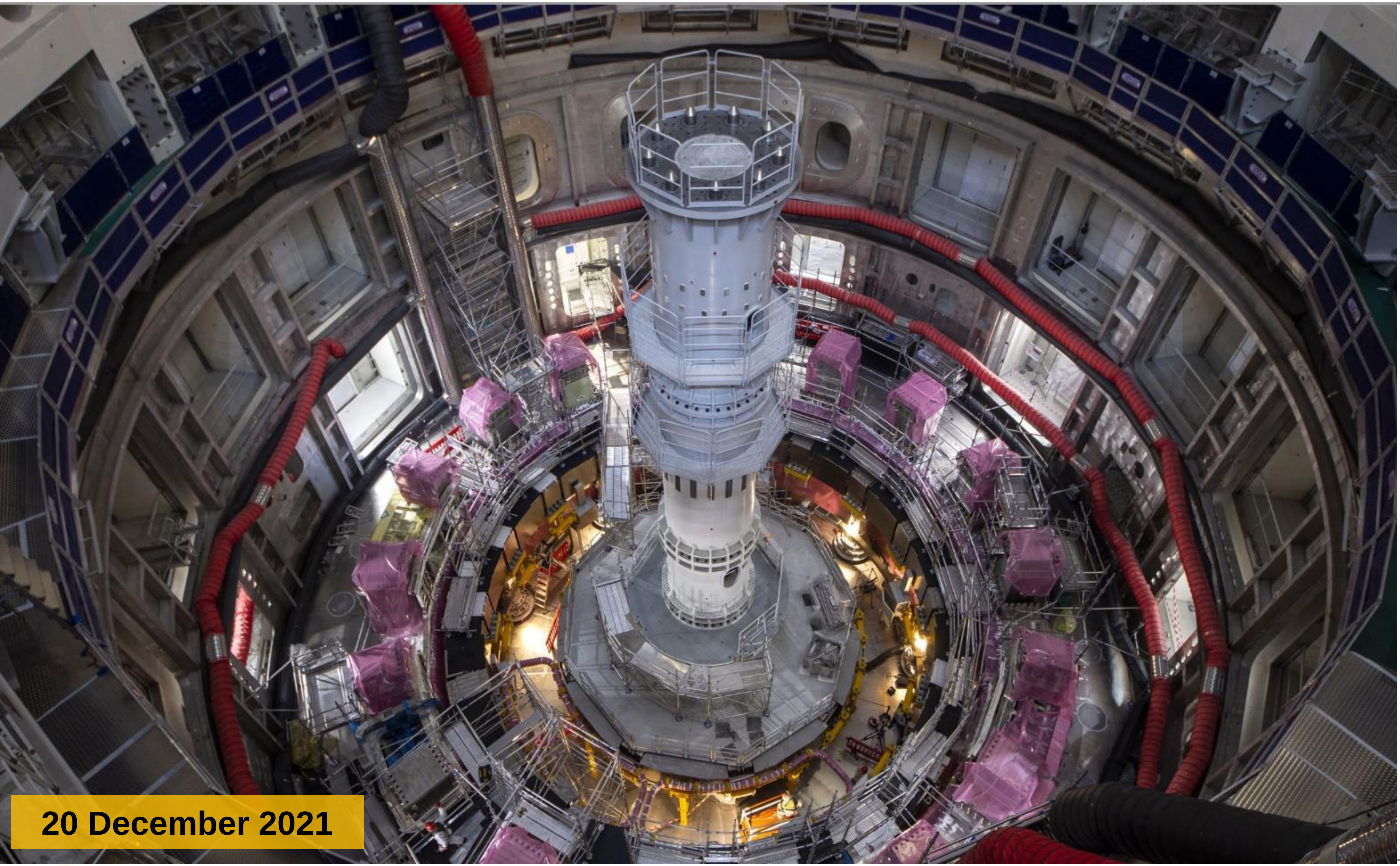
21 October 2021

Vacuum Vessel Sector combined with 2 TF coils in sub-assembly tool



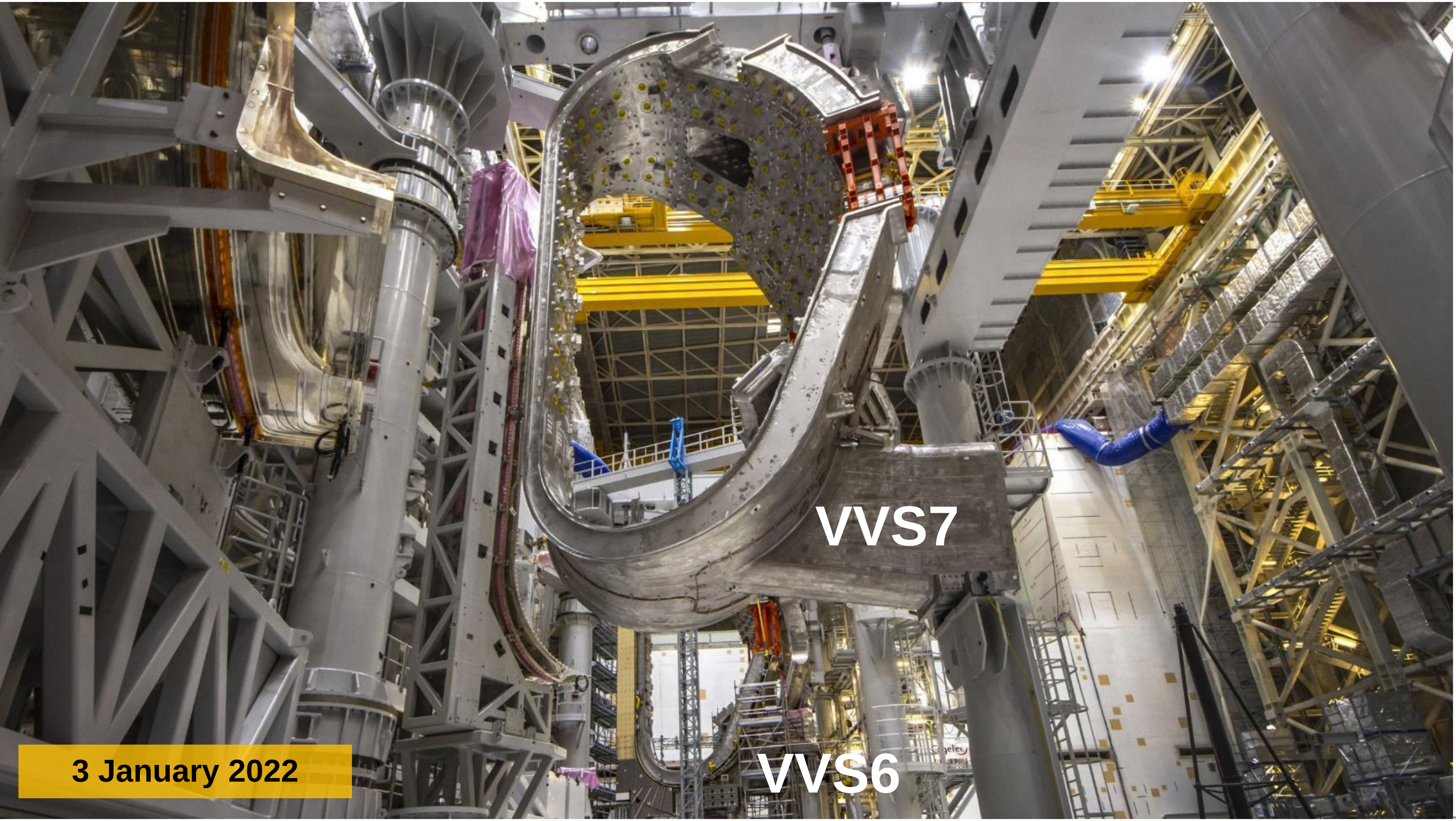
15 November 2021

Pit ready for first sector


20 December 2021

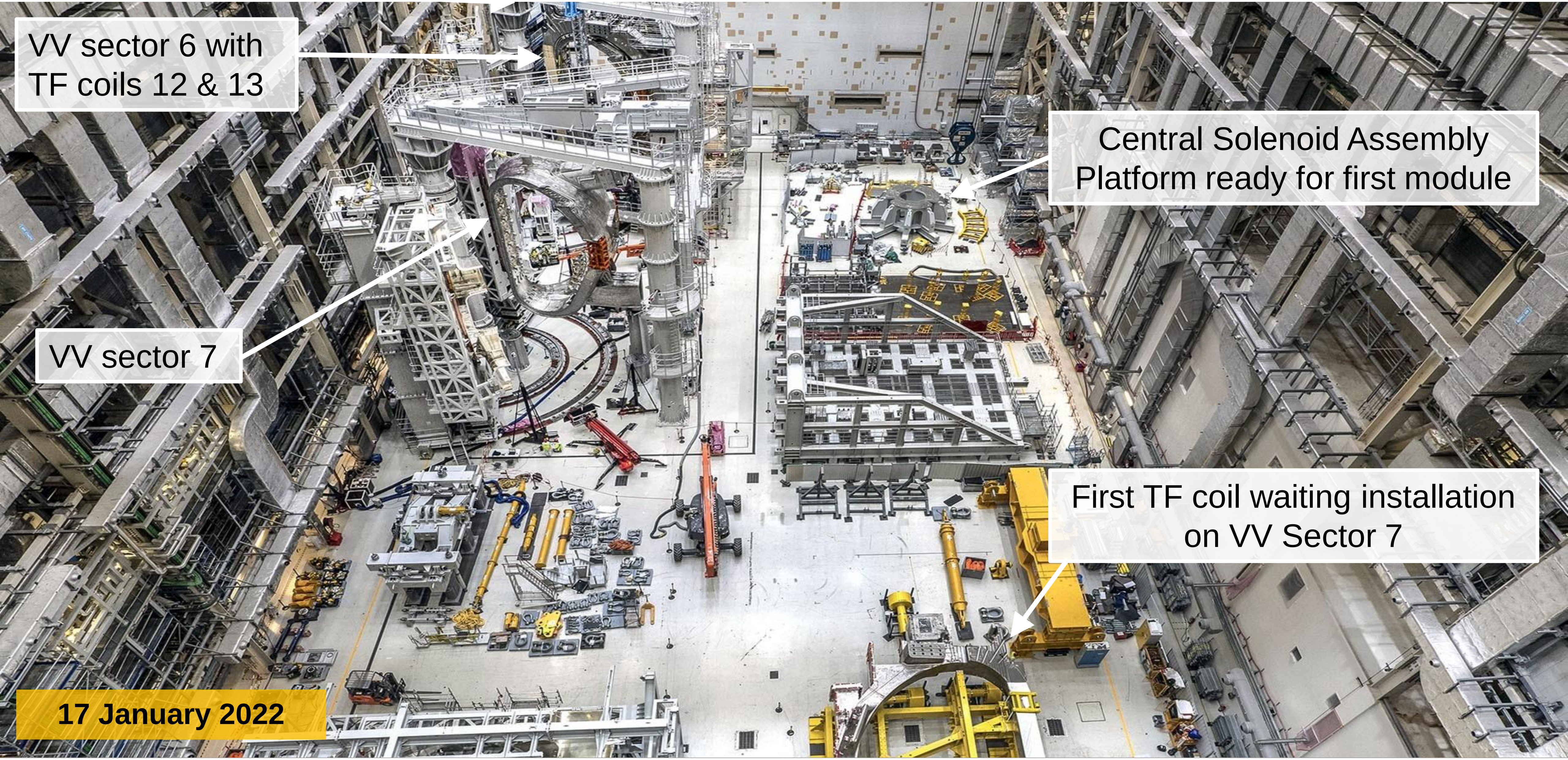
Cryostat lower part, PF5, PF6 and the bottom CC have been installed as well as the central column.

Vacuum Vessel Sectors 6 and 7 both hanging in sub-assembly tools



3 January 2022

Assembly Hall in January 2022



VV sector 6 with TF coils 12 & 13

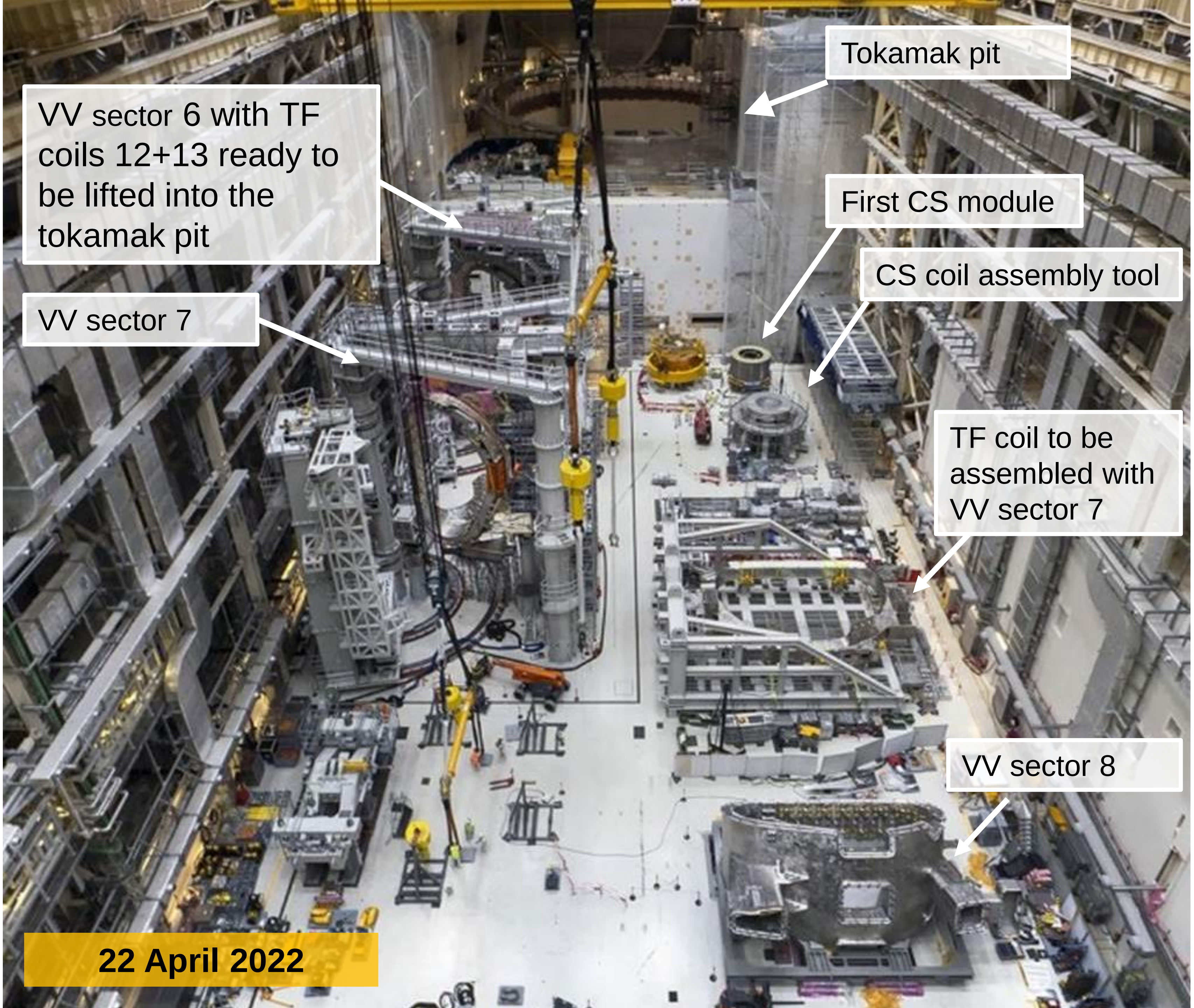
Central Solenoid Assembly Platform ready for first module

VV sector 7

First TF coil waiting installation on VV Sector 7

17 January 2022

Assembly Hall in April



Tokamak pit

VV sector 6 with TF coils 12+13 ready to be lifted into the tokamak pit

First CS module

CS coil assembly tool

VV sector 7

TF coil to be assembled with VV sector 7

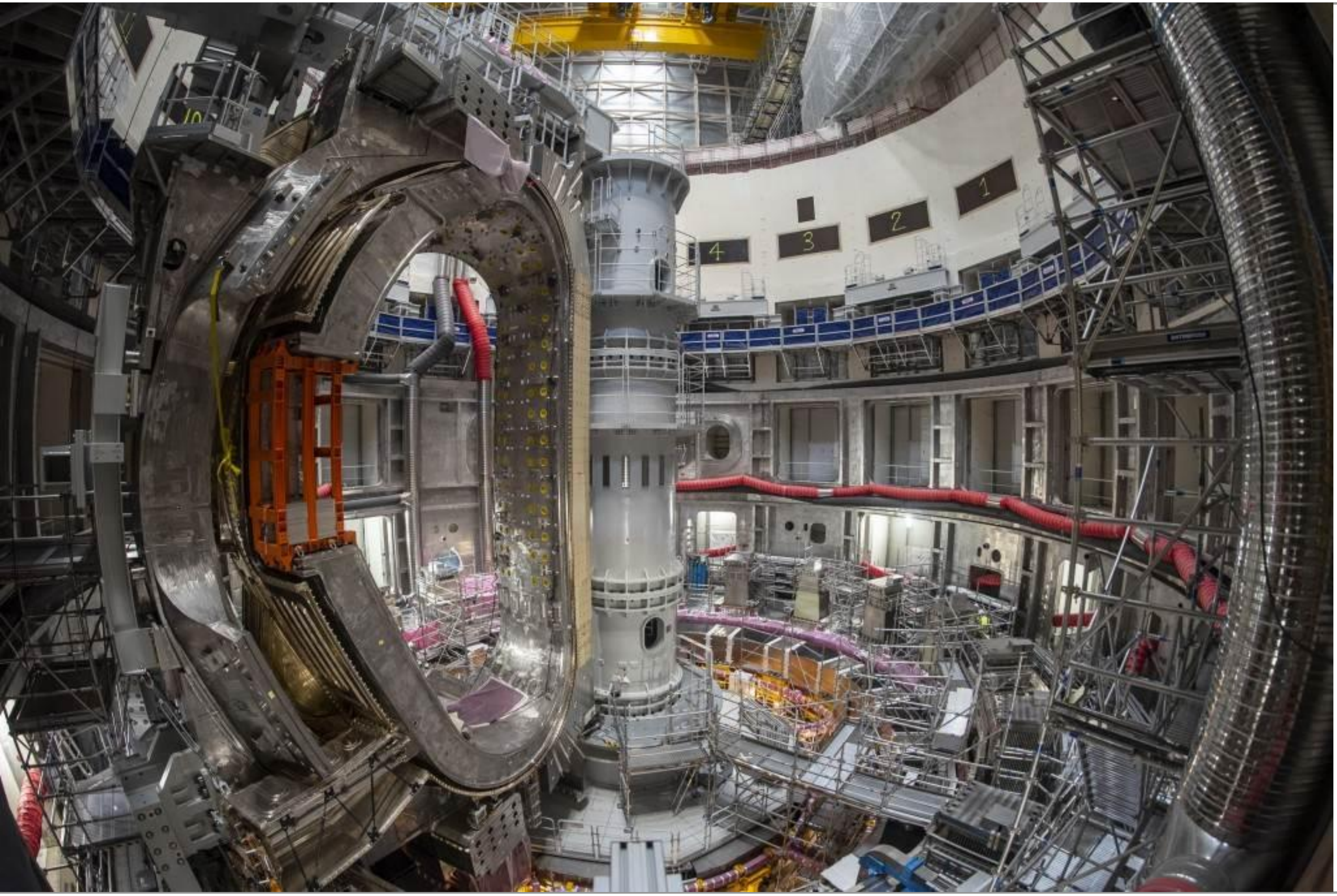
VV sector 8

22 April 2022

The installation of the first sector

On 11 May 2022, the first ITER Sector 6 (VV + 2 TF coils) was installed, into the tokamak pit

First ITER sector installed, 8 more to go ☺



To wrap up

- The ITER PCS will be the first control system that requires the integration of a number of advanced Tokamak control functions into its design.

- The design of the PCS for First Plasma has been completed and is being implemented (i.e. coded), ready for deployment in a few years time, while the design of the PCS for PFPO-1 has commenced.

- The ITER plant assembly is progressing steadily, and the site and device is now >75% complete.

- The ITER Organization and its partners are gearing up to prepare ITER tokamak operation, and the execution of the ITER Research Plan to achieve its goal of Q=10.

List of references 1

Y. Gribov, et al., ITER Physics Basis: Chapter 8: Plasma operation and control, Nucl. Fusion 47 (2007) S385.
https://iopscience.iop.org/article/10.1088/0029-5515/47/6/S08

D. Humphreys, et al., Novel aspects of plasma control in ITER, Physics of Plasmas 22 (2), 021806
https://doi.org/10.1063/1.4907901

M. Walker, et al., Introduction to Tokamak Plasma Control,American Control Conference (2020)
https://ieeexplore.ieee.org/document/9147561

P.C. de Vries, et al., Preparing the Plasma Control System final design for ITER first plasma operations, Fus. Eng. Des 129 (2018) 334.
https://www.sciencedirect.com/science/article/pii/S0920379617309729#bibl0005

J.A. Snipes, et al., Overview of the preliminary design of the ITER plasma control system, Nucl. Fusion 57 (2017) 125001
https://iopscience.iop.org/article/10.1088/1741-4326/aa8177

L. Zabeo, et al.. Fus. Eng. Des. 123 (2017) 522
https://www.sciencedirect.com/science/article/pii/S0920379617306841

W. Treutterer, et al., Towards a preliminary design of the ITER plasma control system architecture, Fus. Eng. Des. 115 (2017) 33.
https://www.sciencedirect.com/science/article/pii/S0920379616307402

G. Raupp, et al., Preliminary exception handling analysis for the ITER plasma control system, Fus. Eng. Des. (2017) 541
https://www.sciencedirect.com/science/article/pii/S0920379617305483

The Guide to the Systems Engineering Body of Knowledge (SEBoK), v1.7.
https://www.sebokwiki.org/wiki/INCOSE_Systems_Engineering_Handbook

M. Cinque, et al., Requirements management support for the ITER Plasma Control System in view of first plasma operations, Fus. Eng. Des 146A (2019) 447
https://www.sciencedirect.com/science/article/pii/S0920379618308536

M. Cinque, et al., Management of the ITER PCS Design Using a System-Engineering Approach, IEEE Trans. Plasma Sci. 48 (2020) 1768
https://ieeexplore.ieee.org/document/8870235

M.L. Walker, et al., The ITER Plasma Control System Simulation Platform, Fus. Eng. Des 96-97 (2015) 716
https://www.sciencedirect.com/science/article/pii/S0920379615000277

M.L. Walker, et al., Assessment of controllers and scenario control performance for ITER first plasma, Fus. Eng. Des 146B (2019) 1853
https://www.sciencedirect.com/science/article/pii/S0920379619303722

List of references 2

E.J. Strait, et al., Progress in disruption prevention for ITER, Nuclear Fusion 59 (2019) 112012.
https://iopscience.iop.org/article/10.1088/1741-4326/ab15de

P.C. de Vries, et al., Requirements for Triggering the ITER Disruption Mitigation System, Fusion Science and Technology 69 (2016) 471.
https://www.tandfonline.com/doi/abs/10.13182/FST15-176

G. Pautasso, The ITER disruption mitigation trigger: developing its preliminary design, Nucl. Fusion 58 (2018) 036011
https://iopscience.iop.org/article/10.1088/1741-4326/aaa137

P.C. de Vries and Y Gribov, ITER breakdown and plasma initiation, Nucl. Fusion 59 (2019) 096043.
https://iopscience.iop.org/article/10.1088/1741-4326/ab2ef4

T. Ravensbergen, et al., Density control in ITER: an iterative learning control and robust control approach, Nucl. Fusion 58 (2018) 016048
https://iopscience.iop.org/article/10.1088/1741-4326/aa95ce/meta

M.D. Boyer and E. Schuster, Nonlinear burn condition control in tokamaks using isotopic fuel tailoring, Nucl. Fusion 55 (2015) 083021.
https://iopscience.iop.org/article/10.1088/0029-5515/55/8/083021

A. Pajares and E. Schuster, Nonlinear burn control using in-vessel coils and isotopic fueling in ITER,Nucl. Fusion 59 (2019) 096023.
https://www.sciencedirect.com/science/article/pii/S0920379617301916

V. Graber and E. Schuster, Assessment of the burning-plasma operational space in ITER by using a control-oriented core-SOL-divertor model, Fus. Eng. Des. 71 (2021) 11251
https://www.sciencedirect.com/science/article/abs/pii/S0920379621002921

ITER Research Plan
https://www.iter.org/doc/www/content/com/Lists/ITER%20Technical%20Reports/Attachments/9/ITER-Research-Plan_final_ITR_FINAL-Cover_High-Res.pdf