(Status of) The ITER project

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Outline

- **Physics and technology goals of ITER**
- **Principal components**
- **Status of the site and assembly**
- **Additional site developments and considerations**

ITER is a major (€15bn) collaboration in fusion energy research by seven international partners

- **Partners: EU (+ Switzerland and UK), China, India, Japan, Russian Federation, South Korea, USA**

- **Overall program objective: demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes**
- **Principal goal: design, construct and operate a tokamak experiment at a scale satisfying objectives**

ITER is a major (€15bn) collaboration in fusion energy research by seven international partners

- Partners: EU (+ Switzerland and UK), China, India, Japan, Russian Federation, South Korea, USA

ITER is designed as a burning (D-T) plasma experiment with significant α-particle heating

(energy production not required)

- Overall program objective: demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

- Principal goal: design, construct and operate a tokamak experiment at a scale satisfying objectives

ITER's project challenges are significant

- Unprecedented size and technology: large and heavy components, challenging to be built by industry (one of a kind pieces)
- Highly integrated components, built in different parts of the world: quality assurance, machine interface, integration
- Total cost is approx. 15 bn Euros: political issue (in particular during current economic turndown), projects cap/ management
- Long time scales, including 10 years of construction and 20 years of operation: political commitment, maintenance periods are expected to be lengthy and difficult

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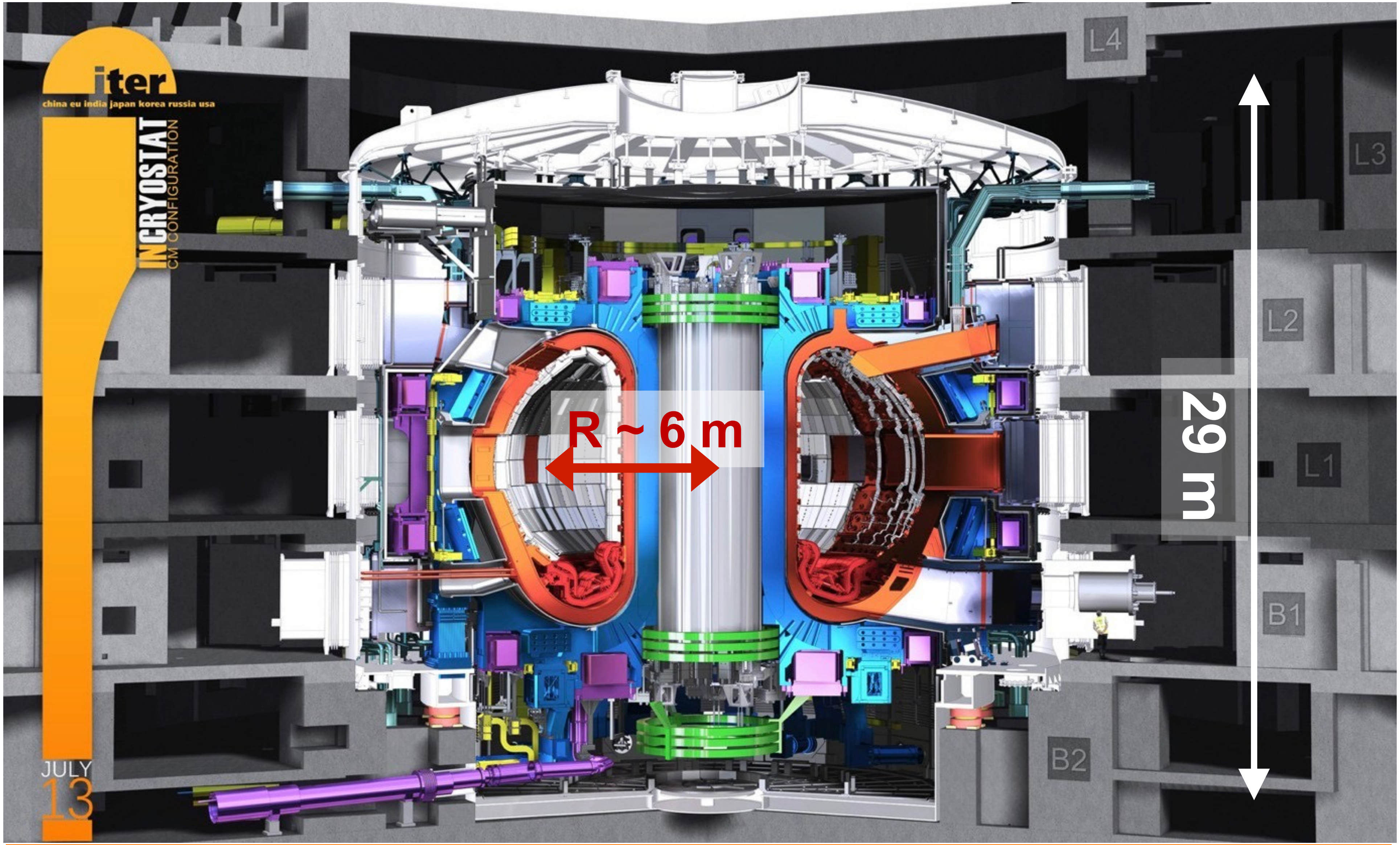
ITER is primarily an experiment, but also a major technology test bed

⇒

Essential step toward DEMO

(or demonstration that tokamaks do not work)

ITER is a large-scale tokamak (R_{major} ~6 m), with superconducting coils, and thus a (heavy) cryostat



ITER is designed to integrate a burning plasma into the latest and future technology

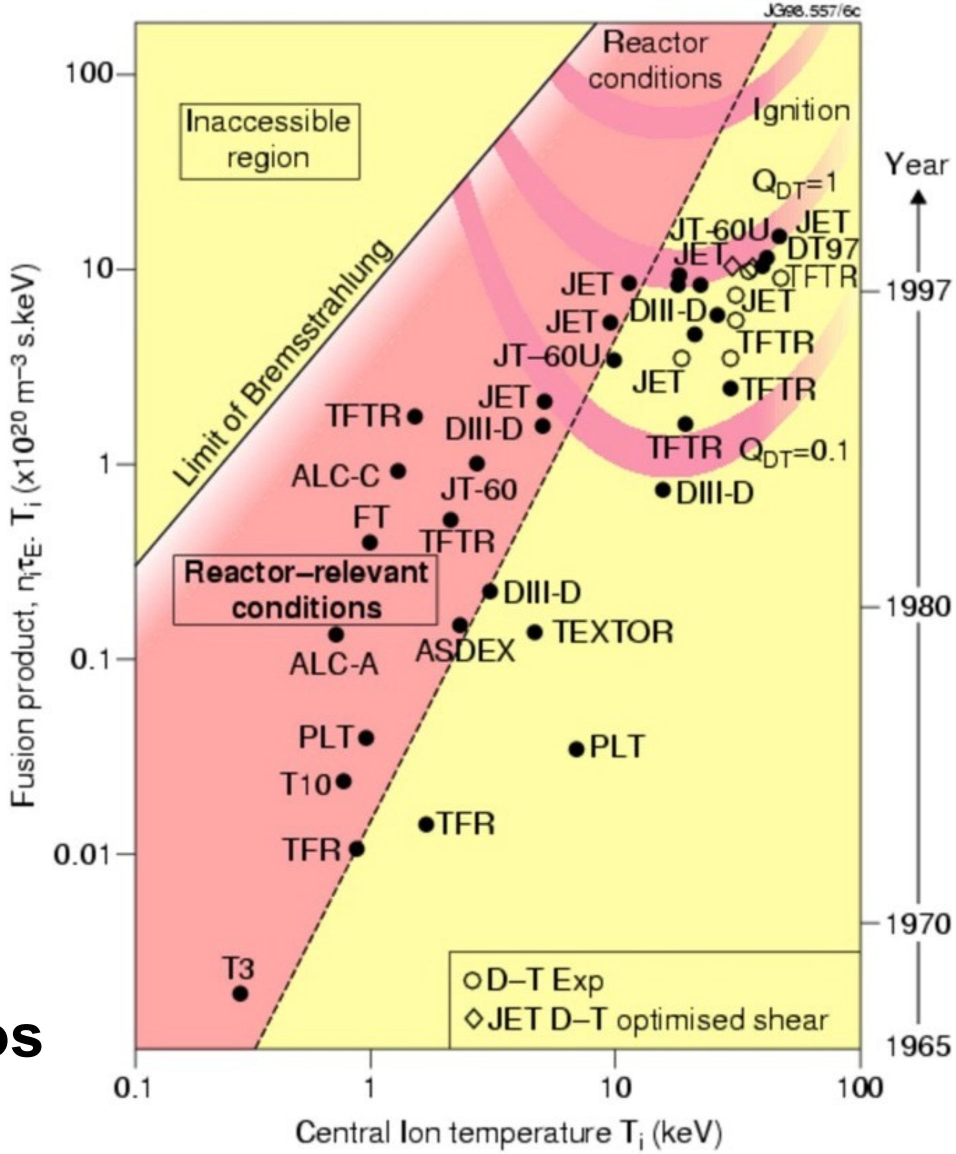
- **Physics goals**
  - Produce significant fusion power ($Q \geq 10$) in long-pulse operations (10s of minutes)
  - Achieve full steady-state operation at moderate fusion power ($Q \sim 10$), retain possibility of exploring ‘controlled ignition’ ($Q \geq 30$)

- **Technology**
  - Demonstrate integrated operation of technology for future fusion power plant
  - Test components required for future power plants
  - Test concepts for a tritium breeding module

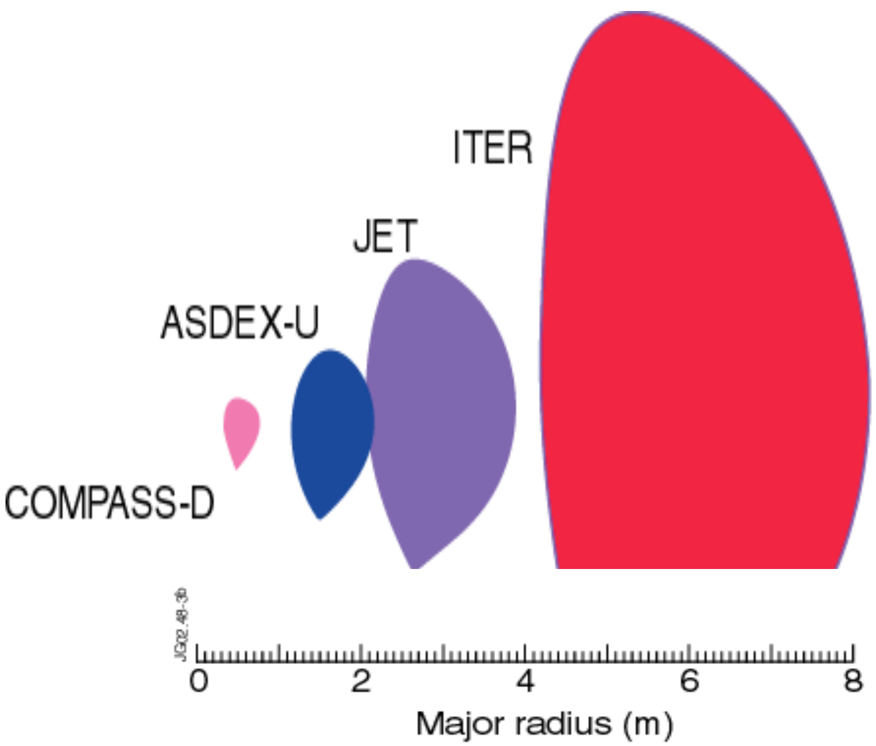
ITER is designed to yield $Q_{DT} \geq 10$ at a fusion power of up 500 MW for up to 500 s

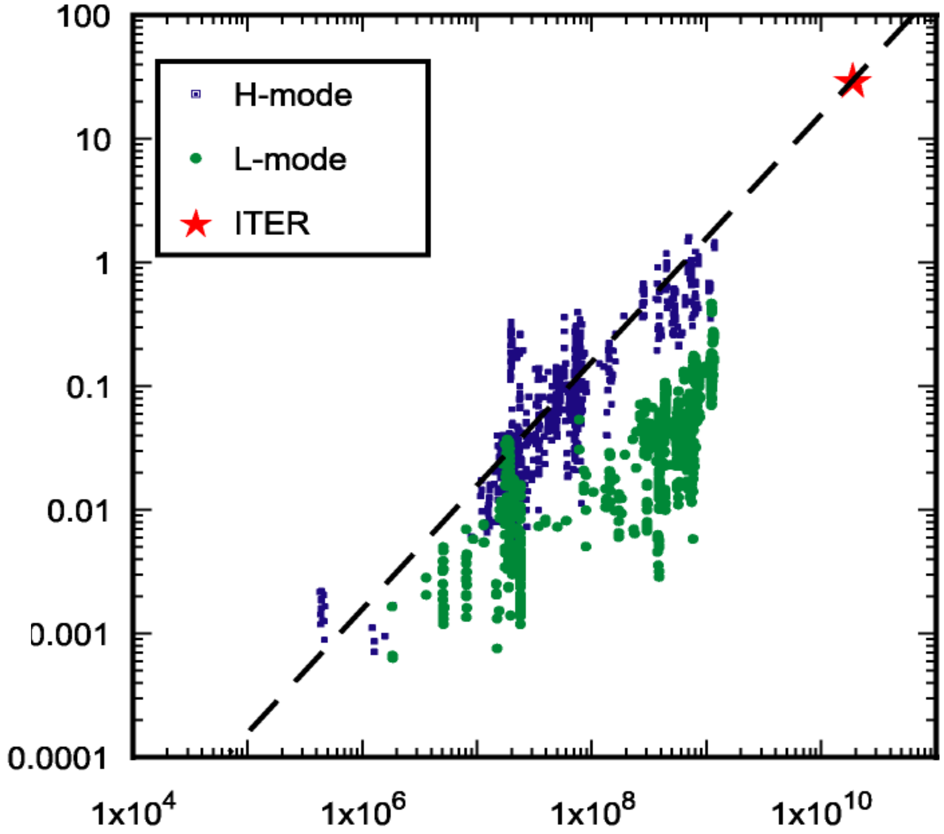
$$Q = \frac{Fusion\ power}{Input\ Power} \sim nT\tau_E$$

- **Existing experiments have reached $nT\tau_E$ ~ $1\text{x}10^{21}$ m^{-3} keV s and Q_{DT} ~ 1**
- **JET and TFTR have produced DT fusion power > 10 MW for 1 s ⇒ 59 MJ in JET-ITER-like wall in 2021**
- **Various ITER reference scenarios (has to be H- mode ⇒ ELMs!)**



Confinement scaling provides an approach to determine the size of ITER





$B^2/2\mu_0 V$ (J) [= W_{mag}]

- **Best performance ($nT\tau_E$) for existing devices versus stored magnetic energy is used to extrapolate to ITER goals**

ITER physics and operation are different to that in present-day tokamaks

- **Plasma is self-heated by fusion α-particles**
  - Non-linearity in total (α-particle + auxiliary) heating power due to dependence on plasma profiles
  - (Some) mode suppression and coupling to fast particle modes
- **ITER requires more advanced plasma control (for position, shape, plasma fueling, heating and stability, power exhaust)**
  - Long time constant for position control (~1 s)
  - Complex control matrix
- **Plasma currents larger than 15 MA**
  - Generation of runaway electron beams, significant disruption forces

ITER physics and operation are different to that in present-day tokamaks

- **High ion fluence (time-integrated plasma flux) to plasma-facing components**
  - Erosion of PFCs and migration of wall material to certain (remote) areas
  - Dust formation
- **Actively cooled systems interfaced with a burning fusion plasma**

ITER physics and operation are different to that in present-day tokamaks

- **Routine operation at Q_{DT}=10 forces operating near/at/ transiently beyond design limits**
  - Robust machine operation mandatory
- **Full nuclear operation (tritium and neutrons)**
  - Retention of tritium in and on PFCs
  - Tritium breeding (test blankets) and re-processing
  - Remote handling for 100% of in-vessel work during nuclear phase
  - Dust inventory
  - Diagnostics
  - Superconducting coil heating
  - Licensing

ITER was licensed as a Basic Nuclear Installation on Nov 10, 2012

- **ITER safety files were formally accepted by French Nuclear Authorities in December 2010**

⇒ Enabled technical evaluation by the Nuclear Safety Regulator (ASN) as well as public evaluation of the system

- **Public inquiry was conducted from June 15 to August 4, 2011 ⇒ on September 19, 2011, the Inquiry Commission issued its Advisory Opinion:**

Arrêtés 2011/200/INB 23/5/11 et 2011/1245/INB 11/7/11 *CONCLUSIONS* *Décision n° E11000025/13*

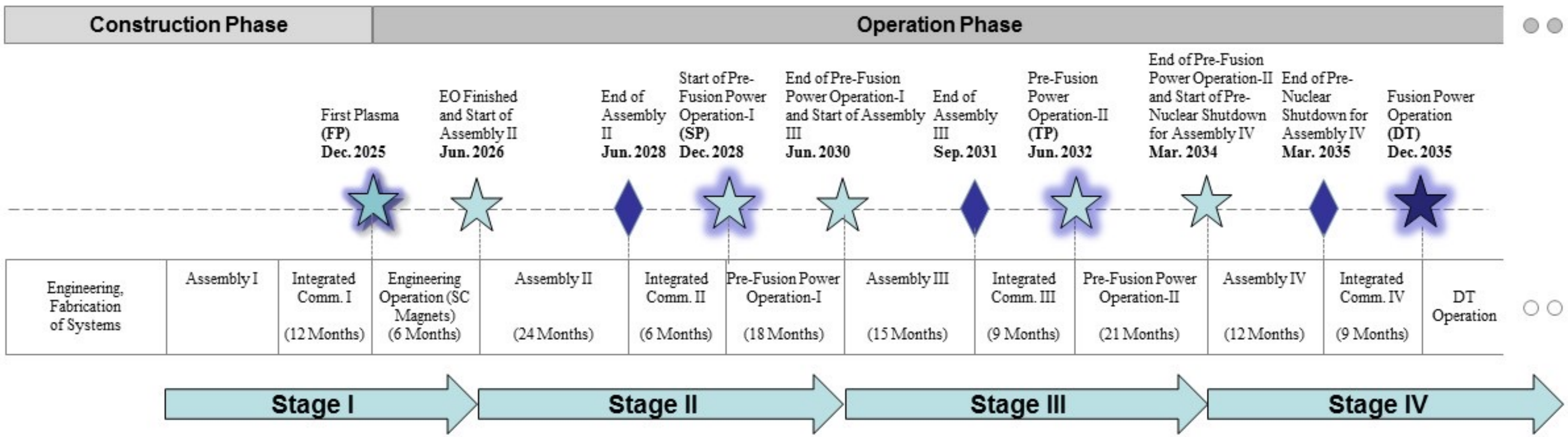
EMET UN AVIS FAVORABLE

A LA POURSUITE DU PROCESSUS D'AUTORISATION DE CREATION DE L'INB ITER

- **On November 10, 2012, the French government published Decree 2012-2048 formally authorizing the creation of the ITER Nuclear Facility**

A revised version of the ITER research plan in 2016 put the start of ITER operation in Dec 2025, and D-T in Dec 2035

- **ITER Research Plan publicly available as technical report (ITR-18-003): https://www.iter.org/technical-reports**
- **Provides definition of required R&D**



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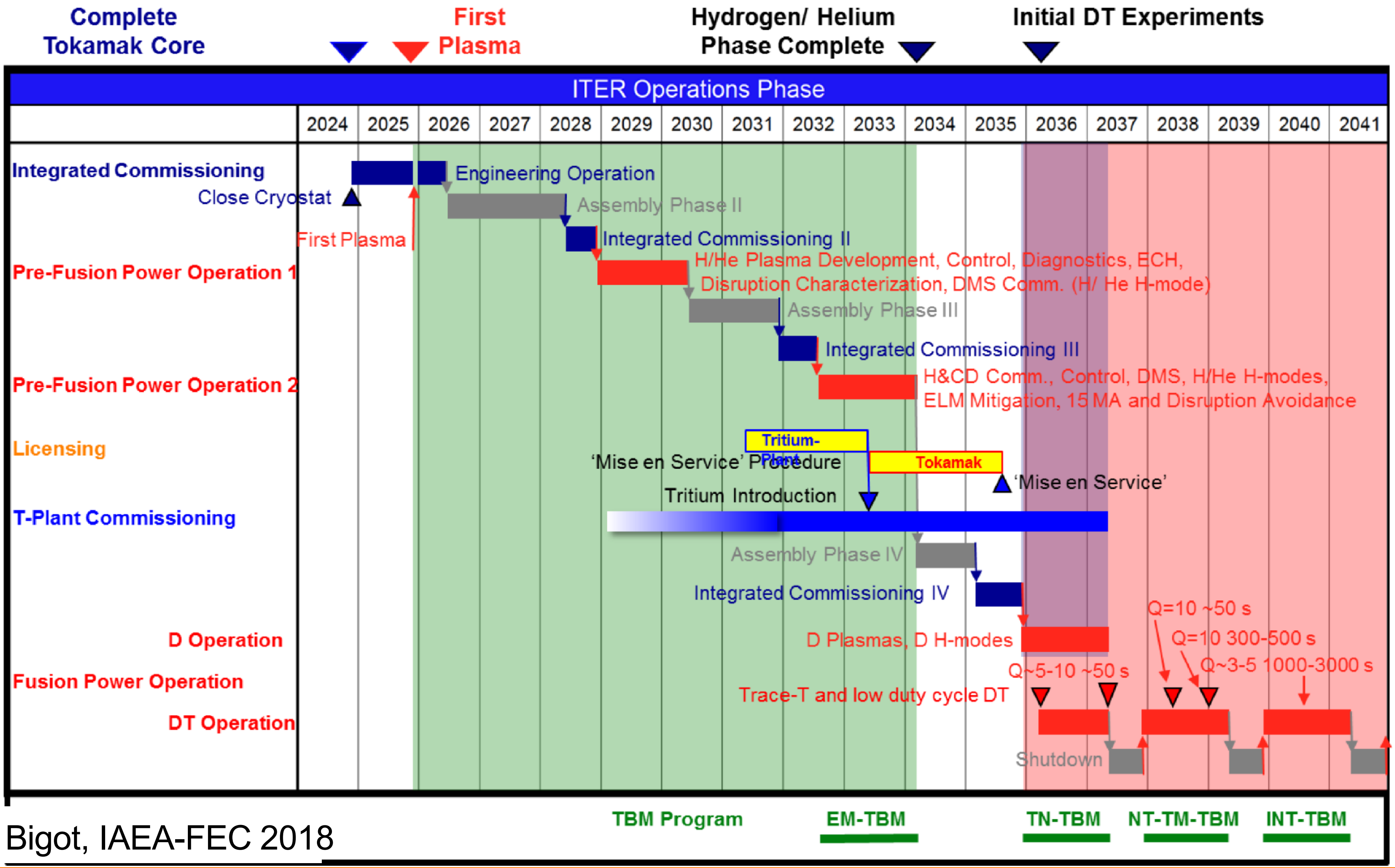
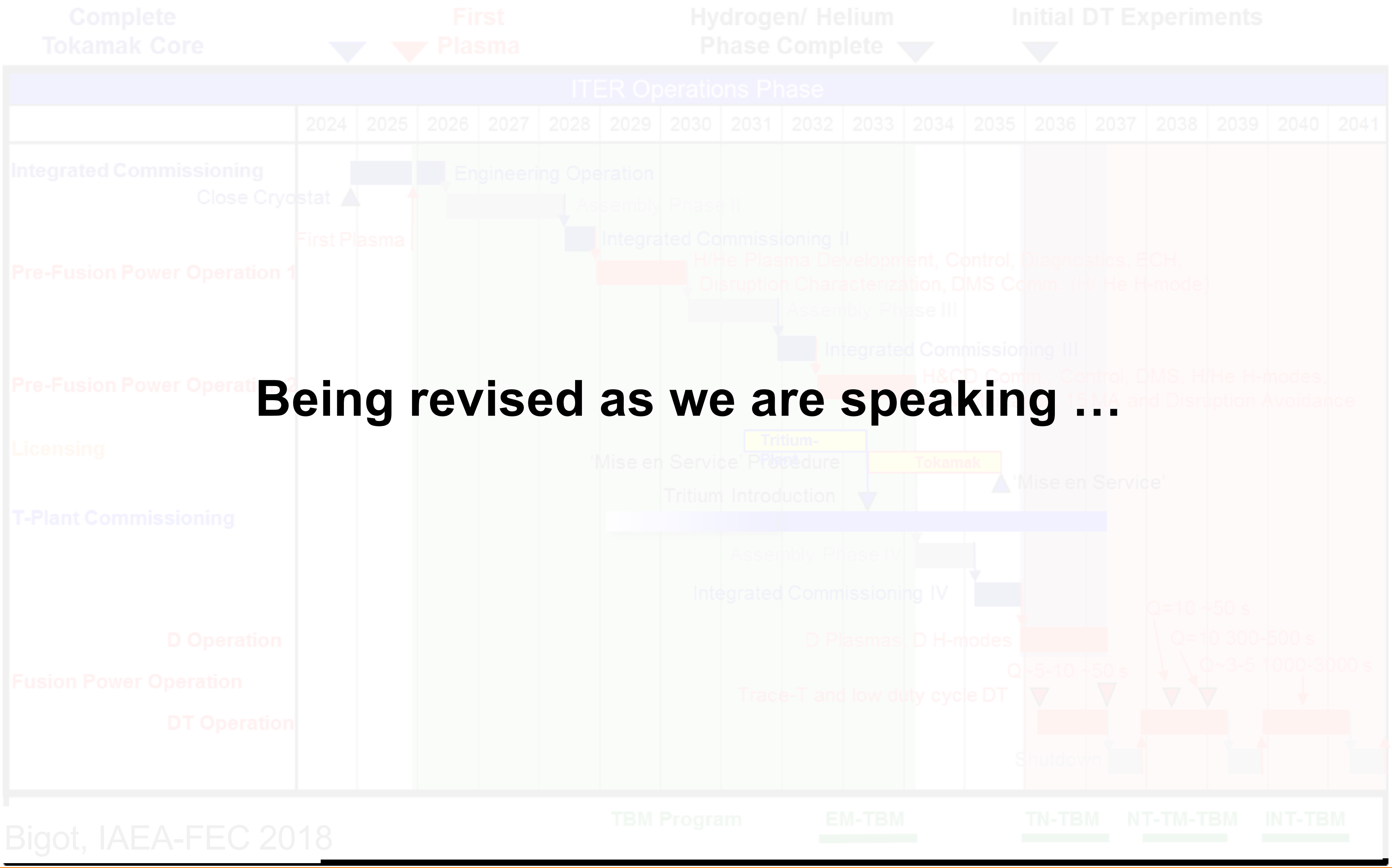


Bigot, IAEA-FEC 2018

A revised version of the ITER research plan in 2016 put the start of ITER operation in Dec 2025, and D-T in Dec 2035



Being revised as we are speaking …

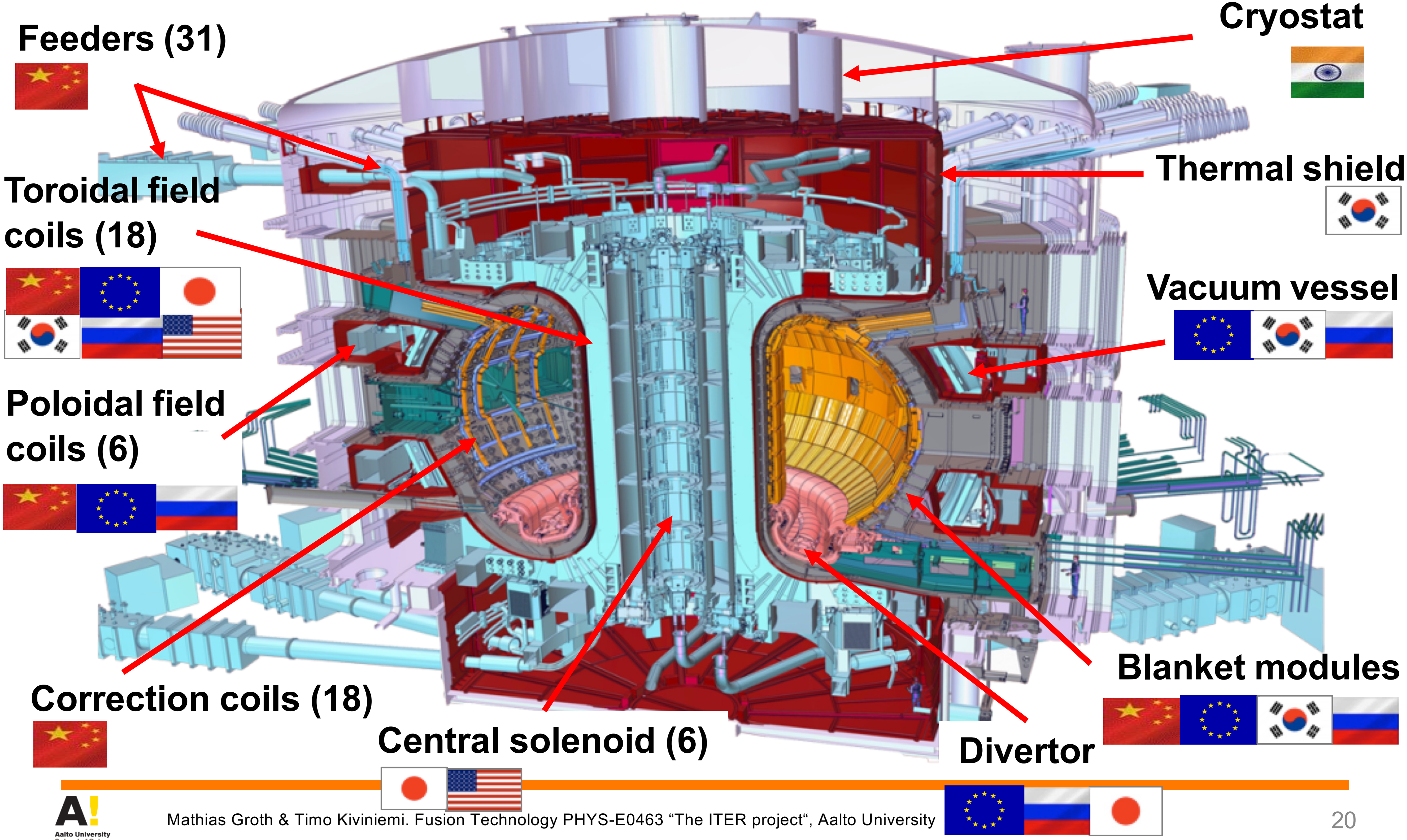
Bigot, IAEA-FEC 2018

Presemo quiz #1

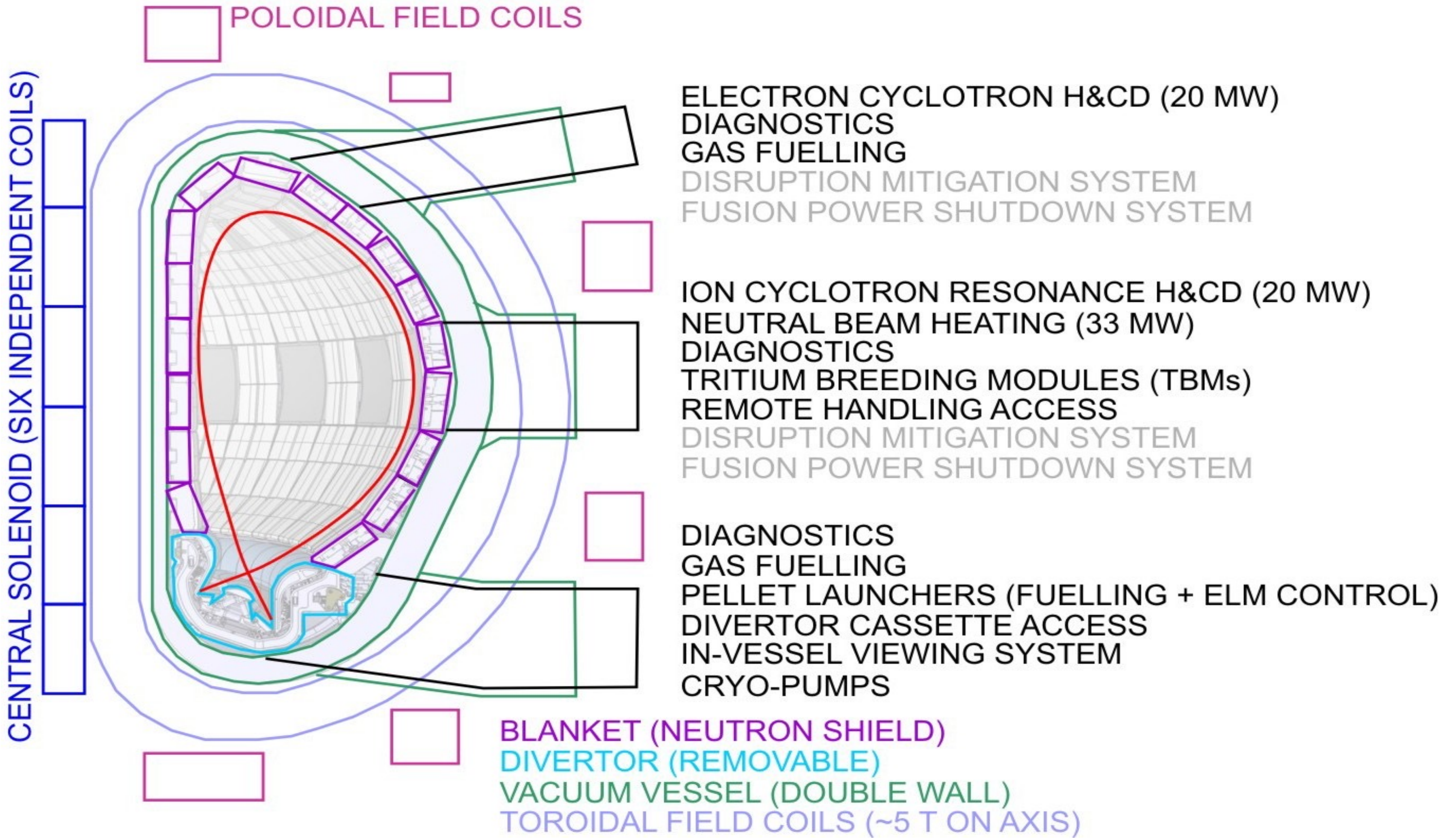
https://presemo.aalto.fi/fet/

Principal components

Distribution of component manufacturing across partners: ITER is shared intellectual property

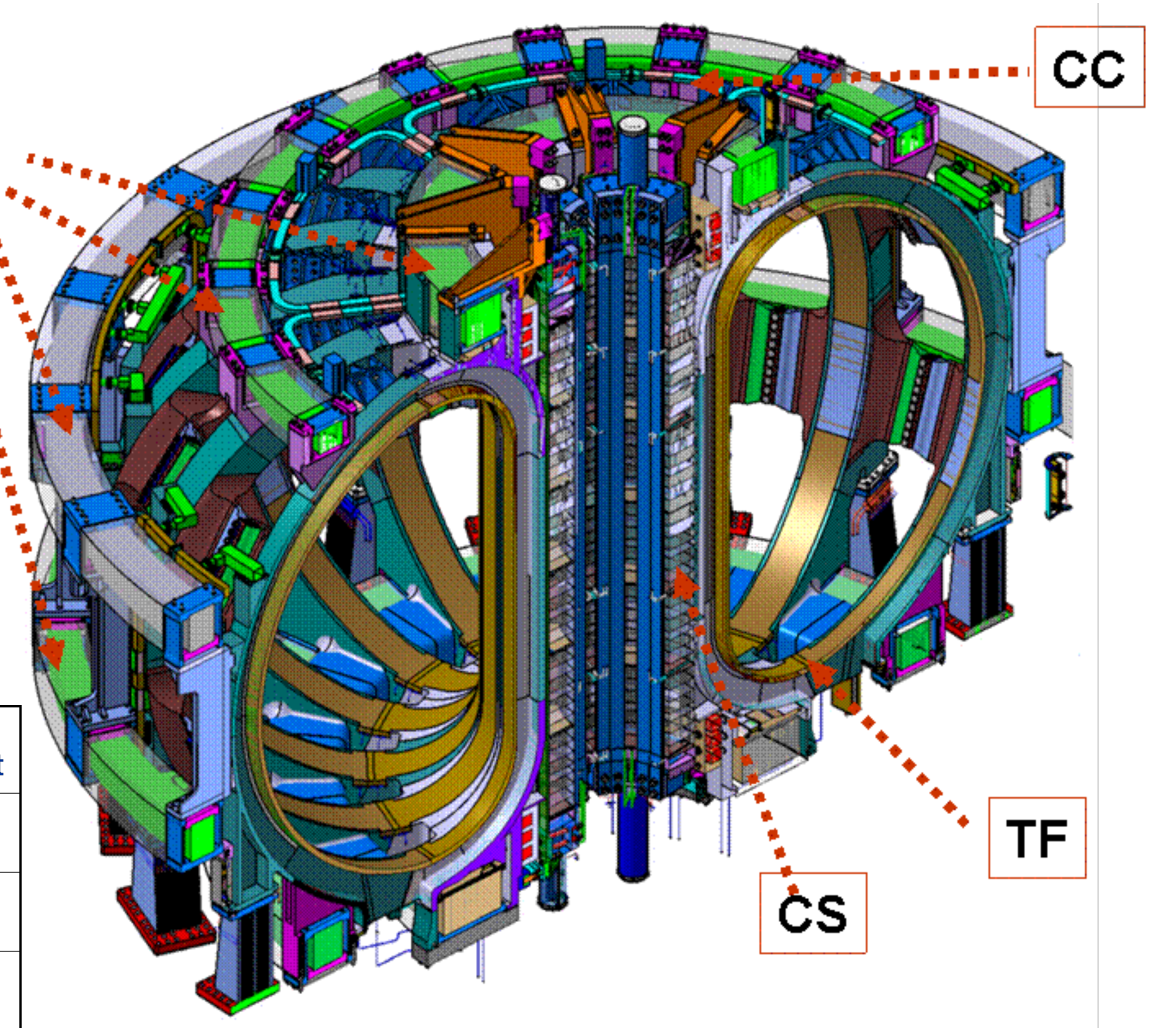


The major components include the vacuum vessel, the magnetic coils, and the heating systems



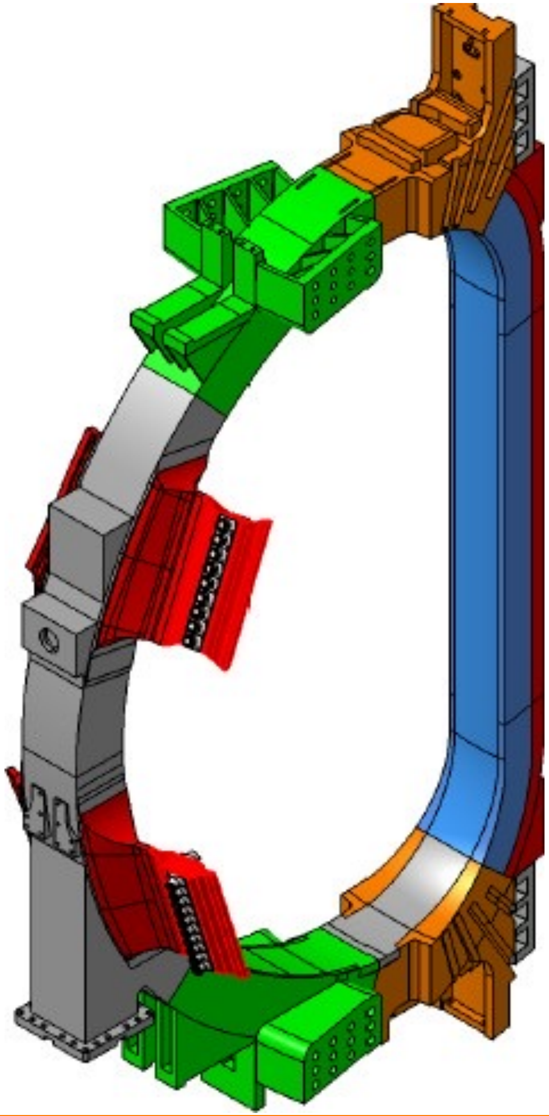
ITER consists of a total of 48 superconducting magnetic coils

- **18 toroidal field coils**
- **6 central solenoid modules**
- **6 poloidal field coils**
- **9 pairs of correction coils**



System	Energy GJ	Peak Field	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

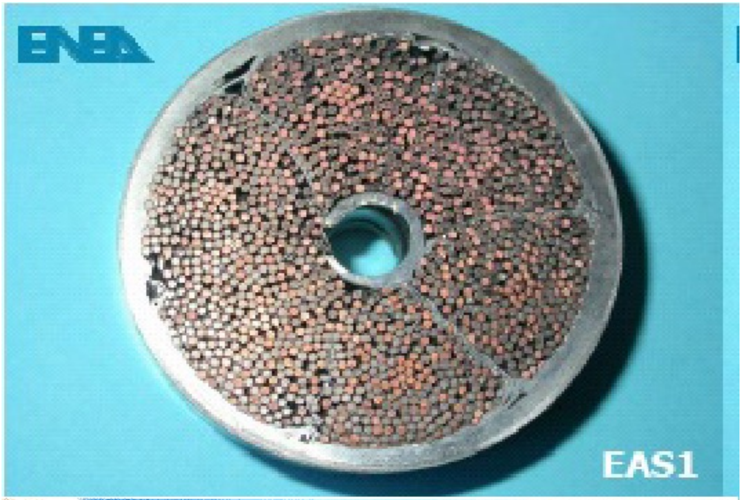
Each toroidal field coils has a total weight of approximately 360 tons, 16 x 9 m in spatial dimensions

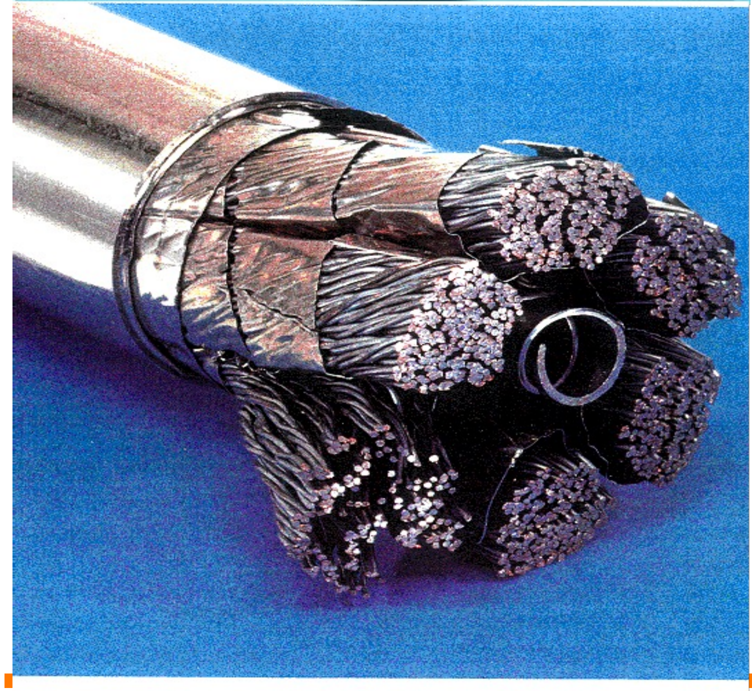


Boeing 747-300: (maximum takeoff weight ~377 t)

- **Fabrication in the EU (Germany, Karlsruhe Institute of Technology) and Japan (Toshiba): 18 coils**

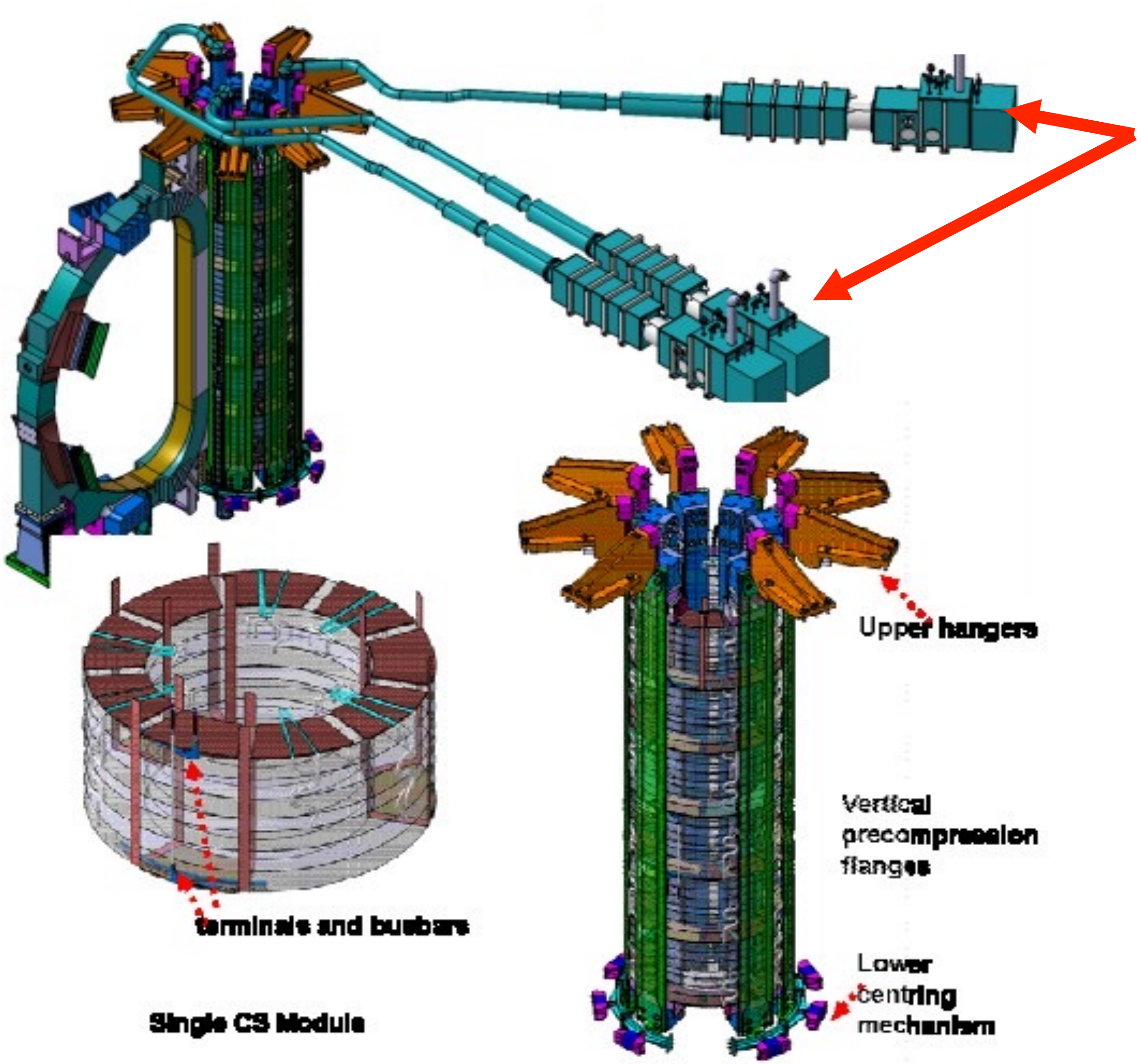
An unprecedented amount of low-temperature (~ 5 K) superconductors is needed





- **~90 km / 450 tons of Nb_3Sn**
- **~ 150,000 km of strand**
- **Operation at ~4.5 K**
- **Peak magnetic field 11.8 T**
- **68 kA peak current in coils**
- **Manufacture in EU, Japan, Russian Federation, China, Korea and US**

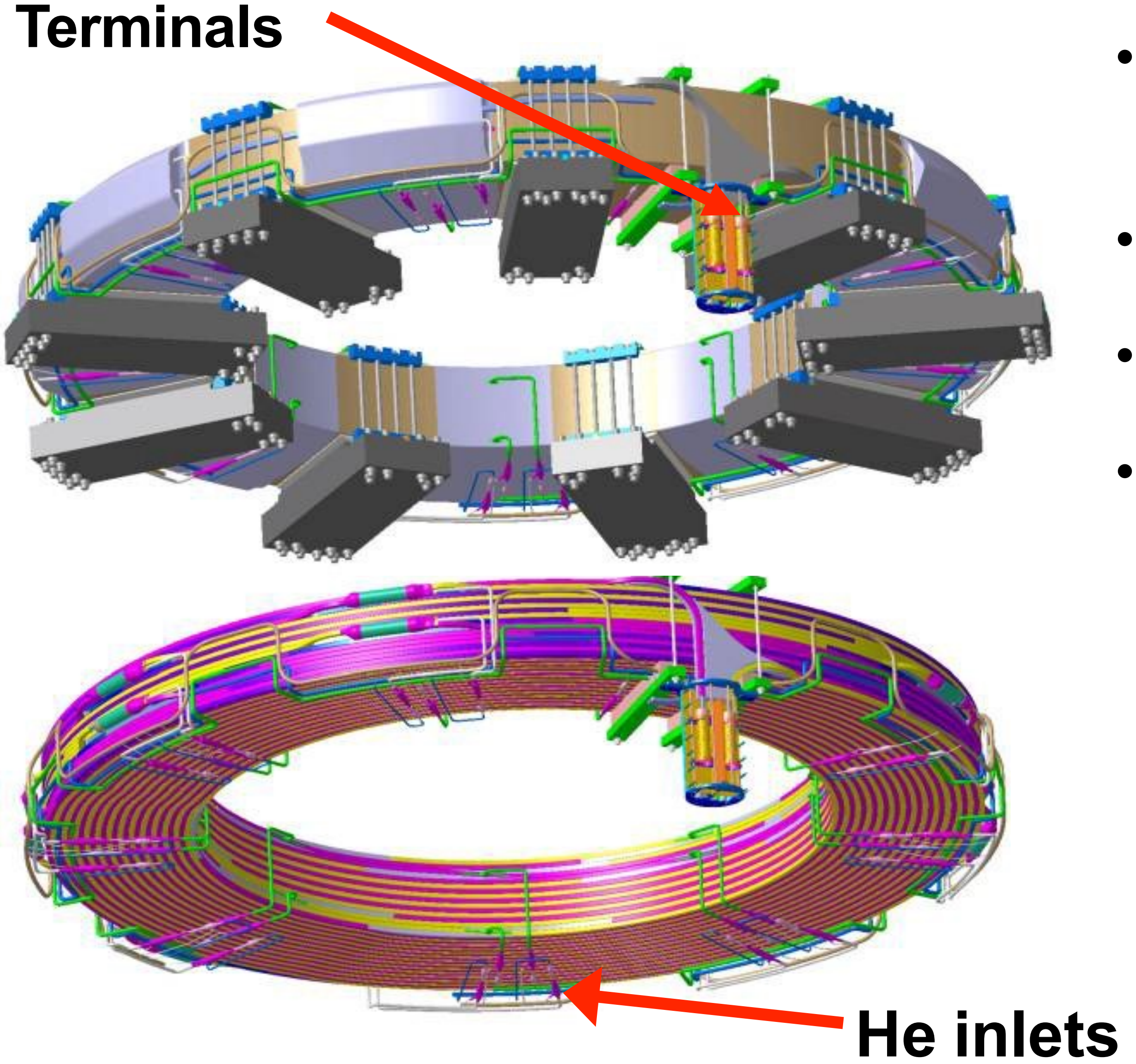
The central solenoid coil stack consists of 6 independently powered modules



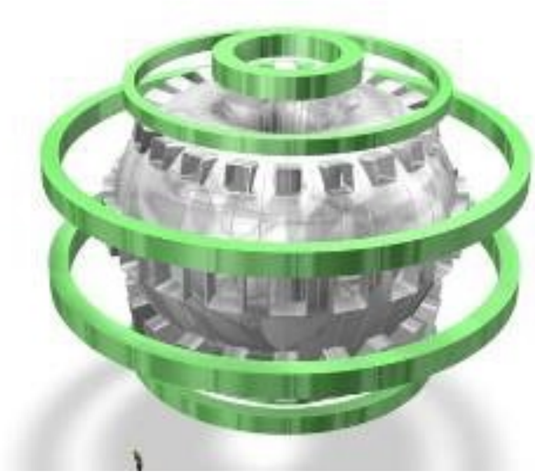
Feeders (CN)

- **Size ~12 m x 4 m**
- **Nb_3Sn conductor**
- **Peak magnetic field 13 T**
- **45 kA peak current**
- **~100 tons**

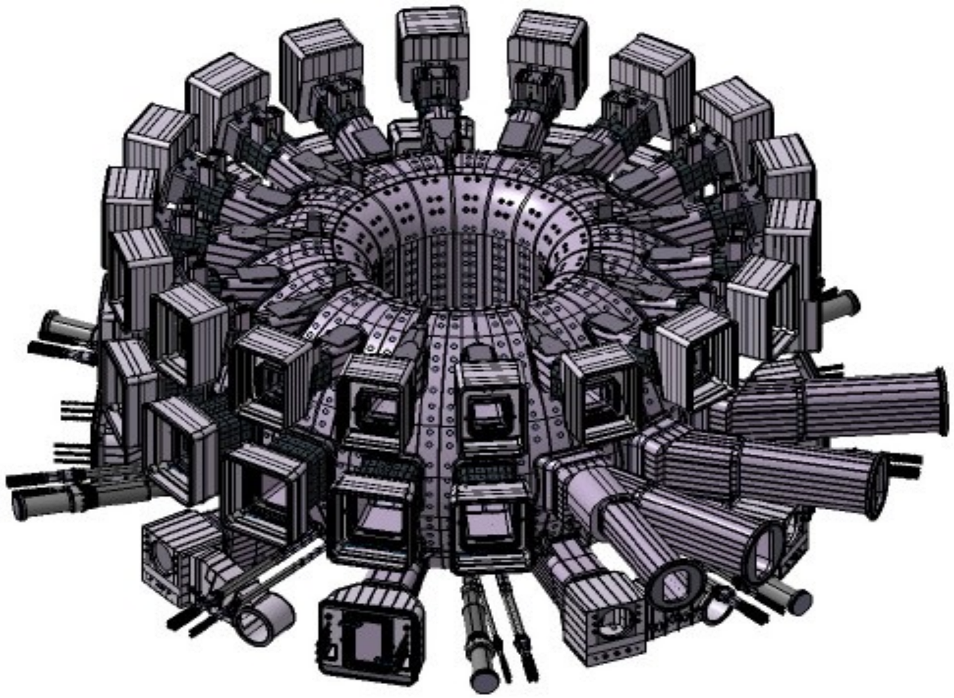
There are 6 poloidal field coils, made of NbTi

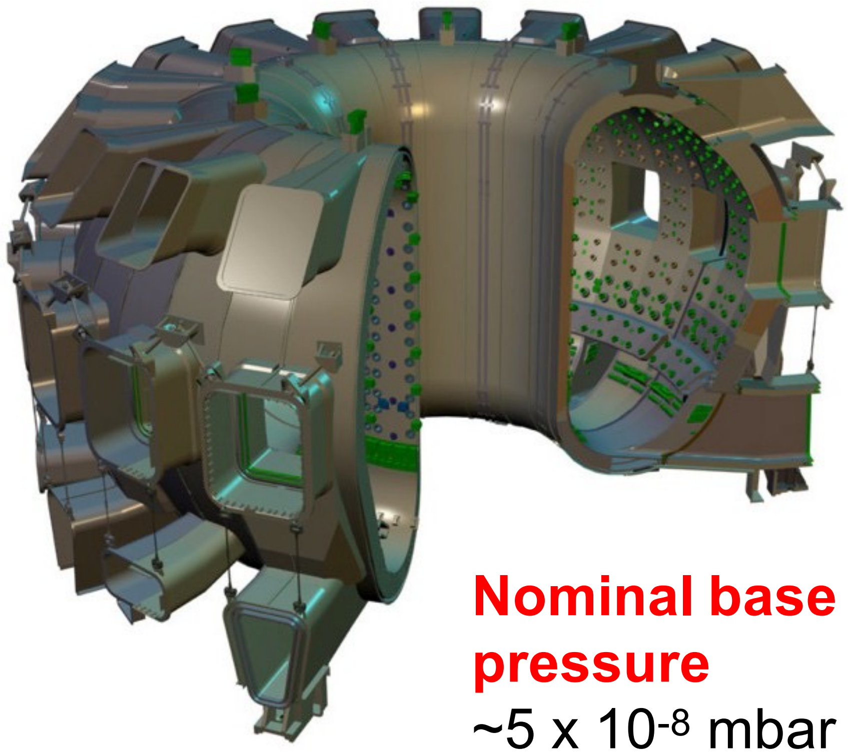


- **Up to 25 m in diameter**
- **6.8 T peak field**
- **55 kA peak current**
- **Manufactured on-site**



The vacuum vessel is a double-walled, stainless steel structure of about 5300 tons



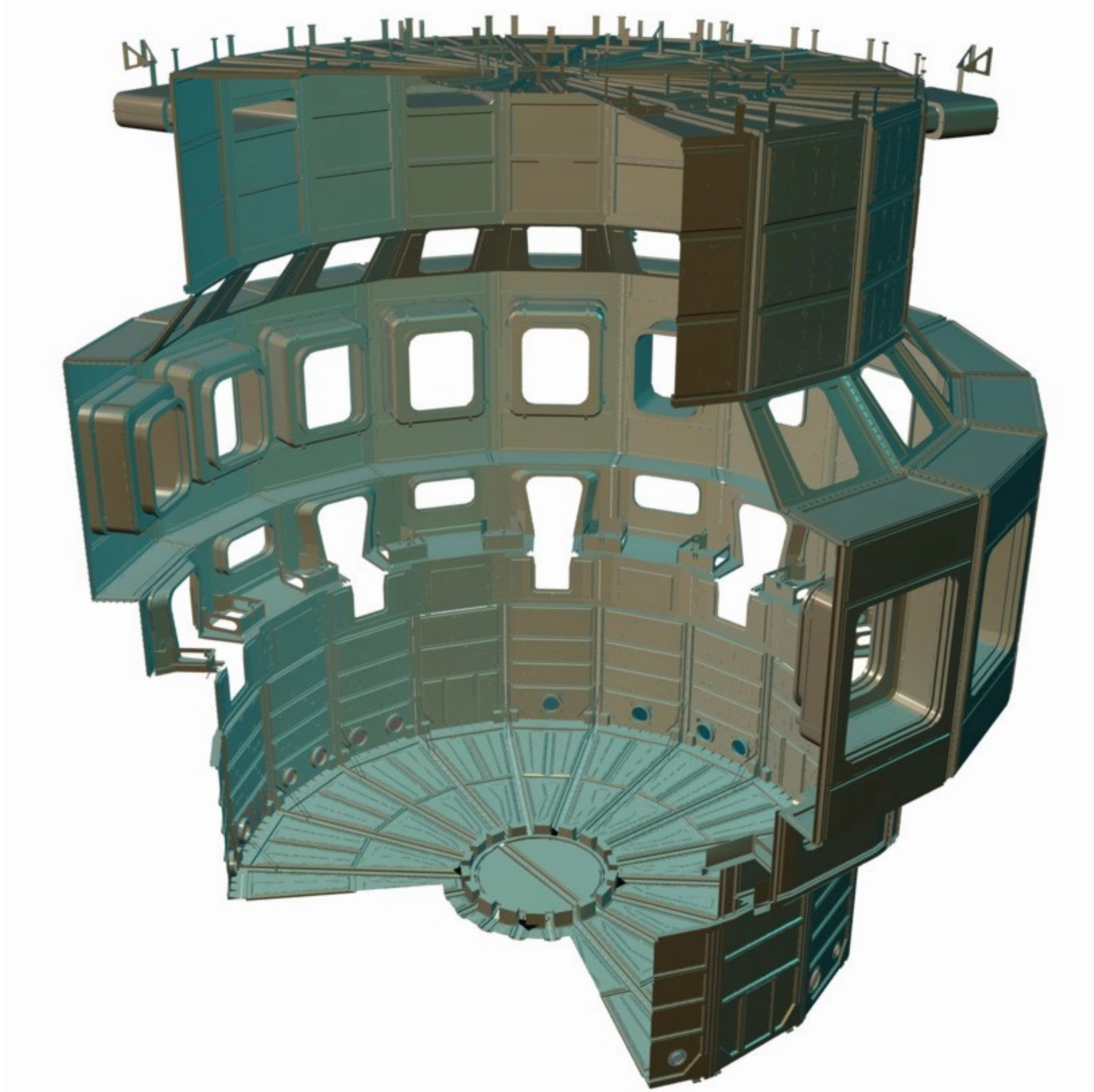


Nominal base pressure

~5 x 10^{-8} mbar

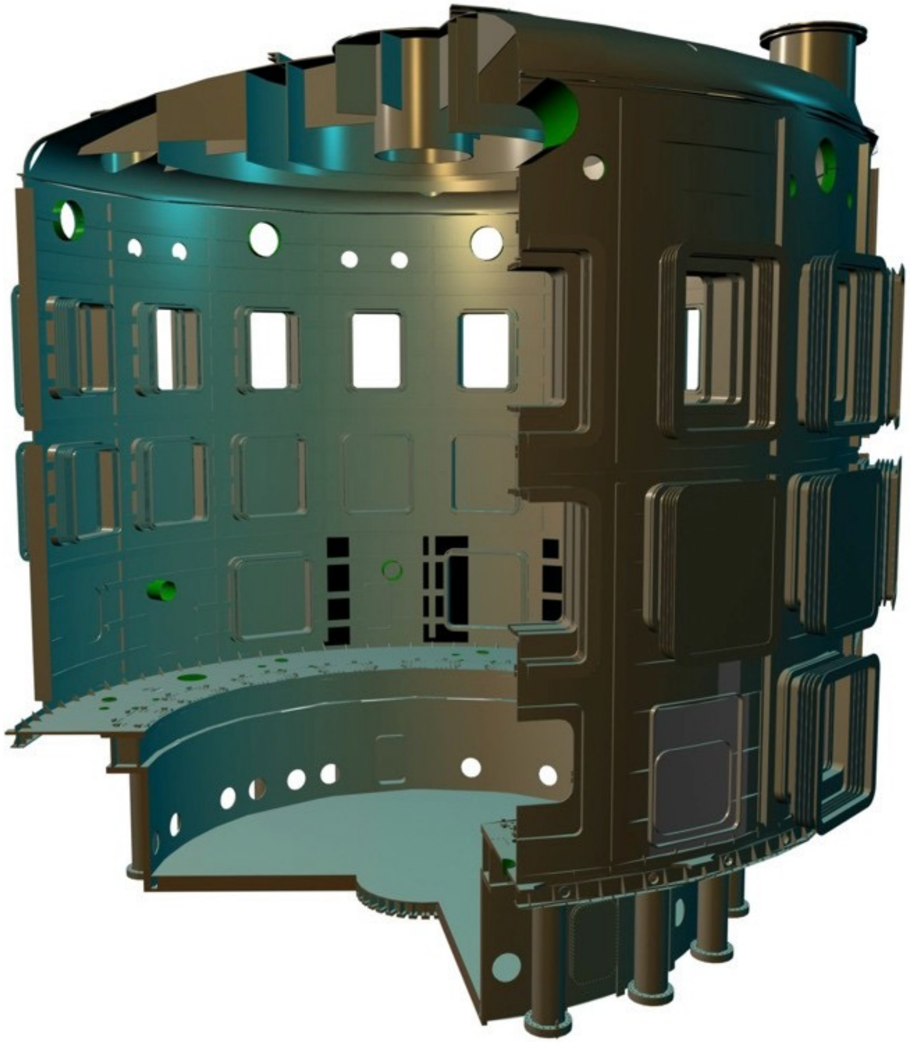
- **19.4 m outer diameter, 11.3 m height**
- **SS 316 L(N)-IG**
- **Primary tritium containment barrier, bakeable to 200 ℃**

The main inner heat shield provides a barrier for thermal loads to the superconducting coils (4.5 K)



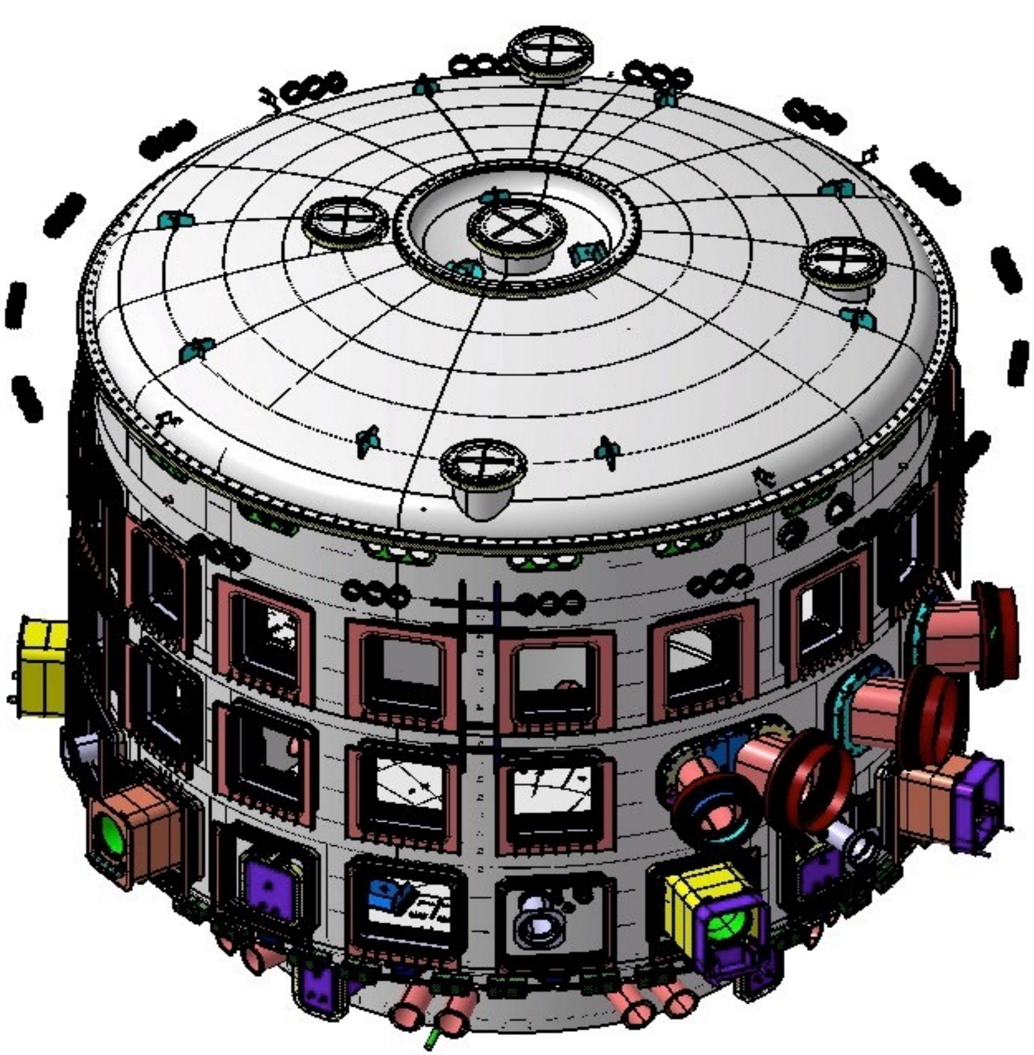
- **Operates at 80 K (gaseous He in cooling pines)**
- **Stainless steel panels are silver coated to reduce emissivity**
- **Total mass ~ 1000 t**
- **Smaller shield isolates TF coils from vacuum vessel**

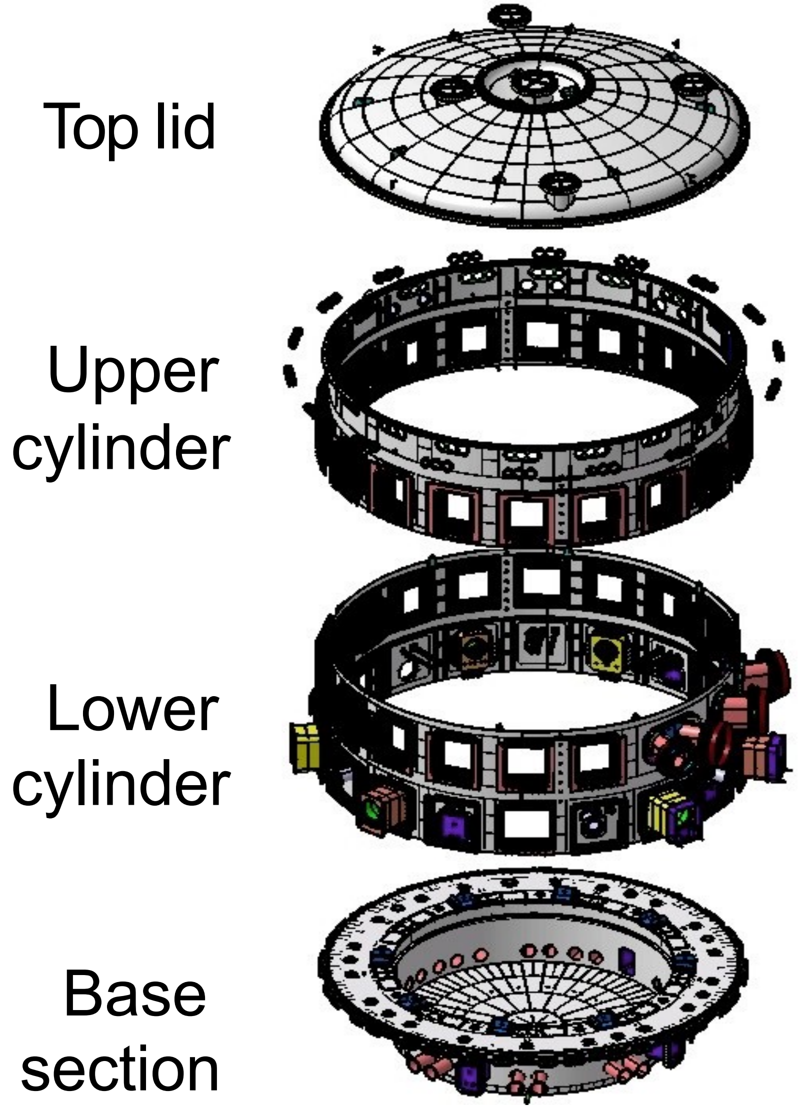
The cryostat provides the vacuum insulation for the superconducting coils



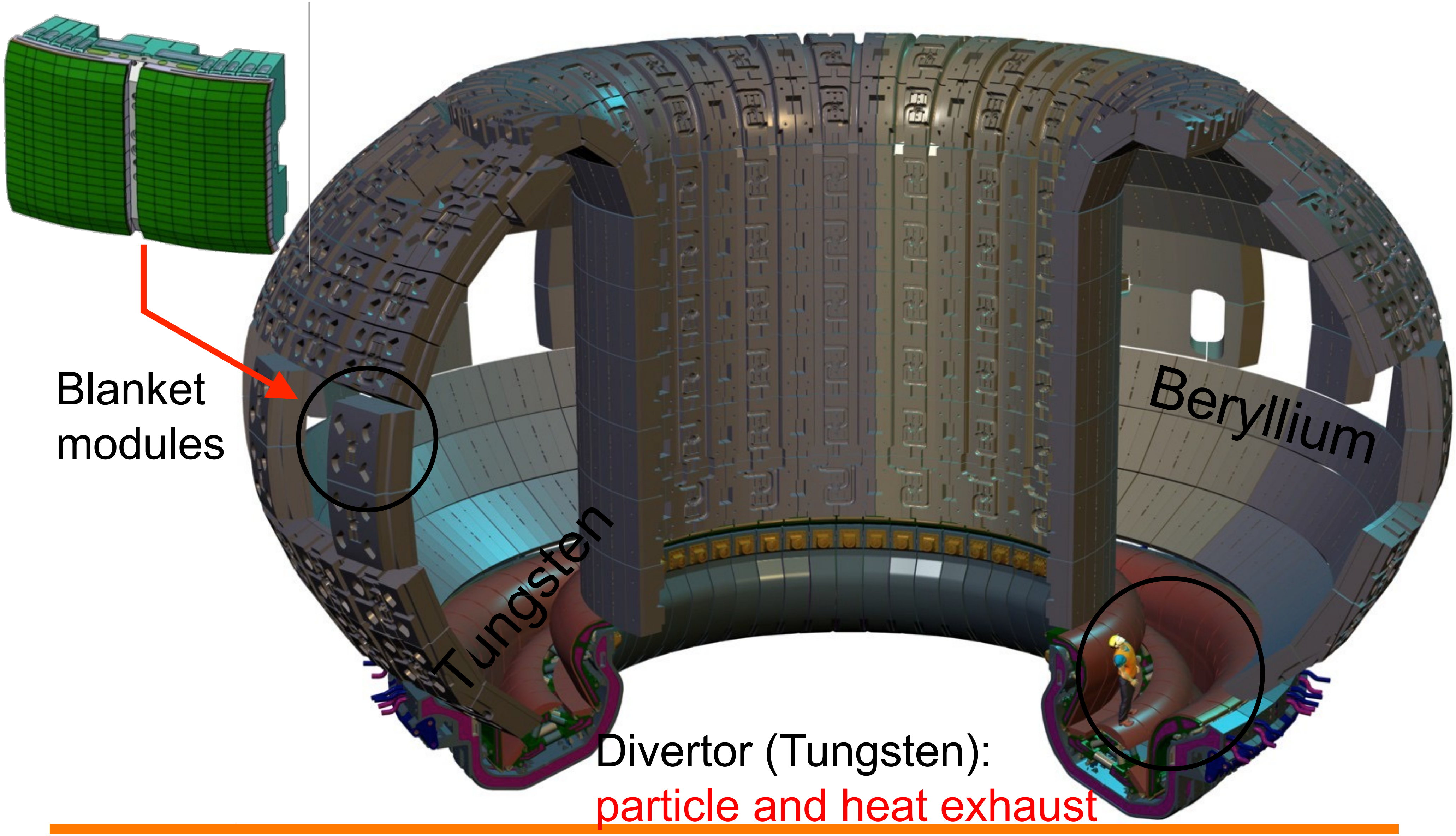
- **29.4 m in diameter,**
- **~29 m in height**
- **Total mass ~ 3500 t**
- **Base pressure < 10-4 mbar**
- **Stainless steel 40 – 180 mm thick**

The cryostat provides the vacuum insulation for the superconducting coils





The first wall, or blanket, provides the interface of the machine to the (burning!) plasma



The power loads to the plasma-facing components in ITER exceed those of space rocket launches

Heavy Water Reactor

Re-entry vehicle

~1 <10

Ariane 5/ Vulcain 2

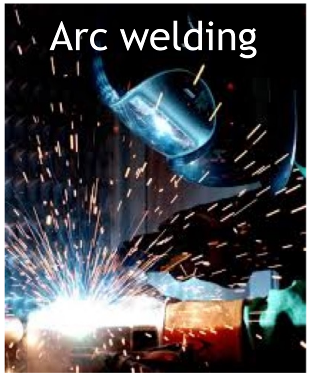
85

ITER transients

2000

Power load [MW/m²]

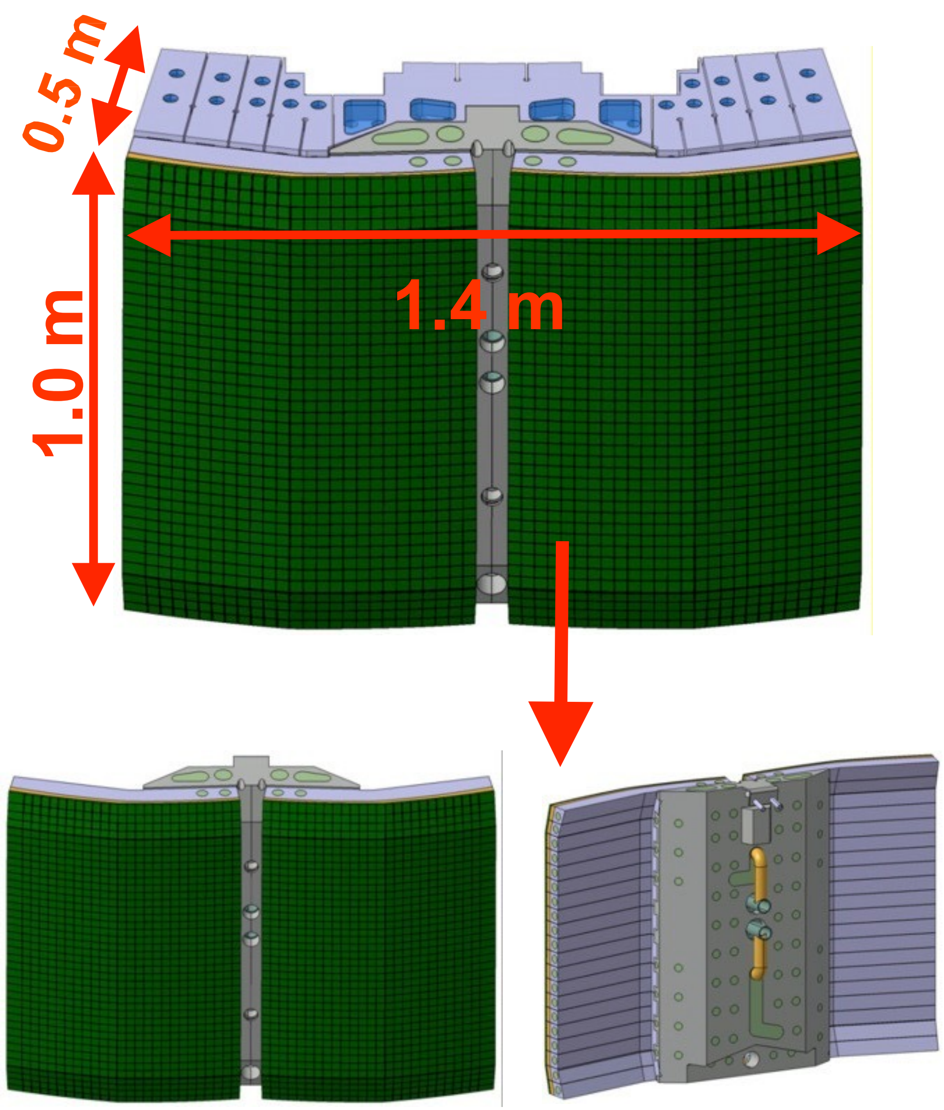
Rolls Royce Trent 900



ITER steady-state

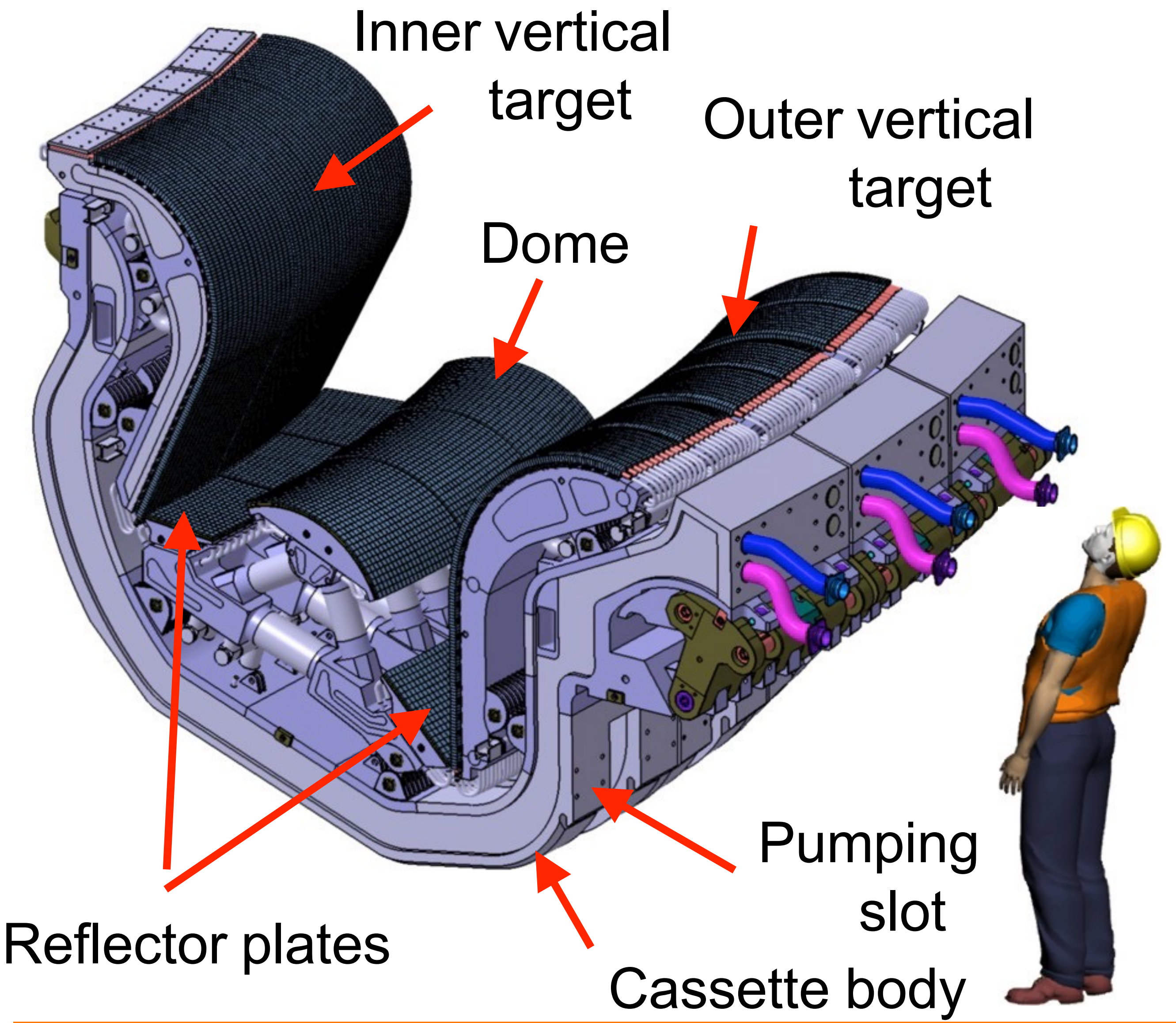
Luce, APS-DPP Oct 2018

The first-wall blanket modules provide both neutron and plasma shielding



- **Semi-permanent massive shield block for neutrons (3.5 t)**
- **Shaped first-wall panels armored with Be**
- **Total number of blanket modules: 440 (1800 t)**

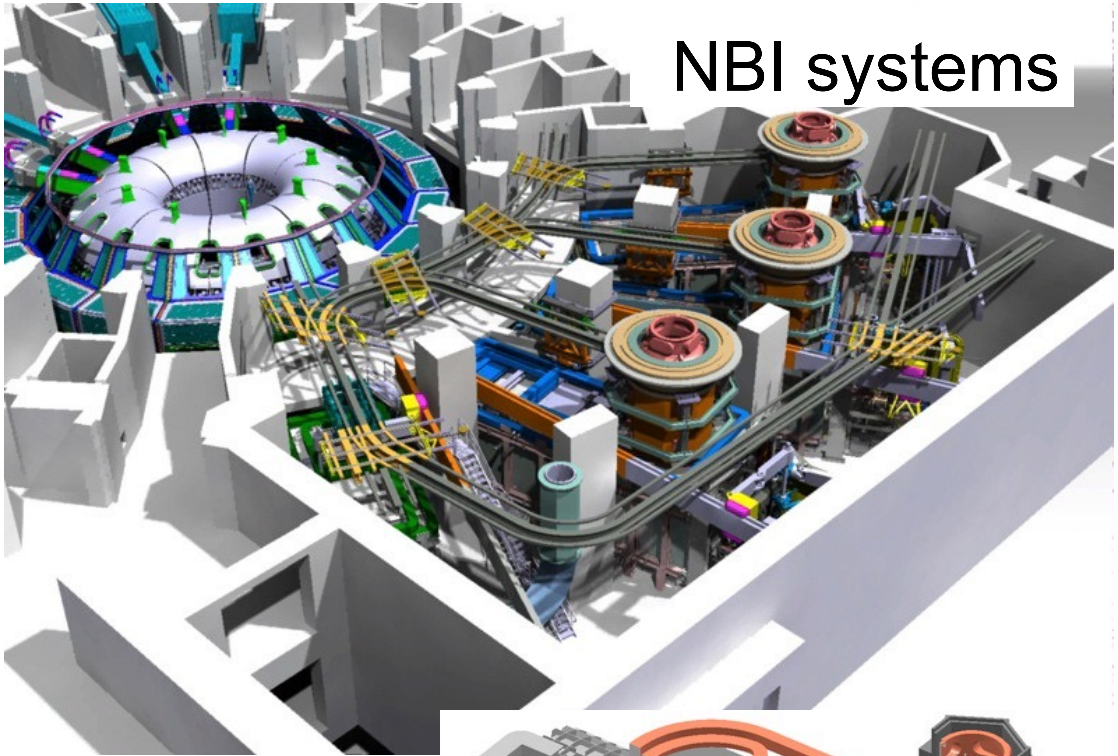
The divertor consists of 54 cassettes (~ 8.7 t each) bakeable to 350 ℃

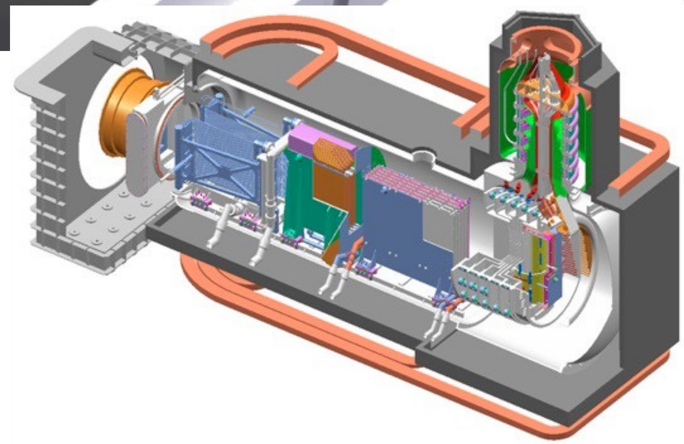


- **4320 actively cooled heat flux components**
- **Divertor PFCs are made of tungsten**
- **Removable cassettes**

Auxiliary power of a total of 50 MW by means of neutral beams and radio frequency heating is foreseen

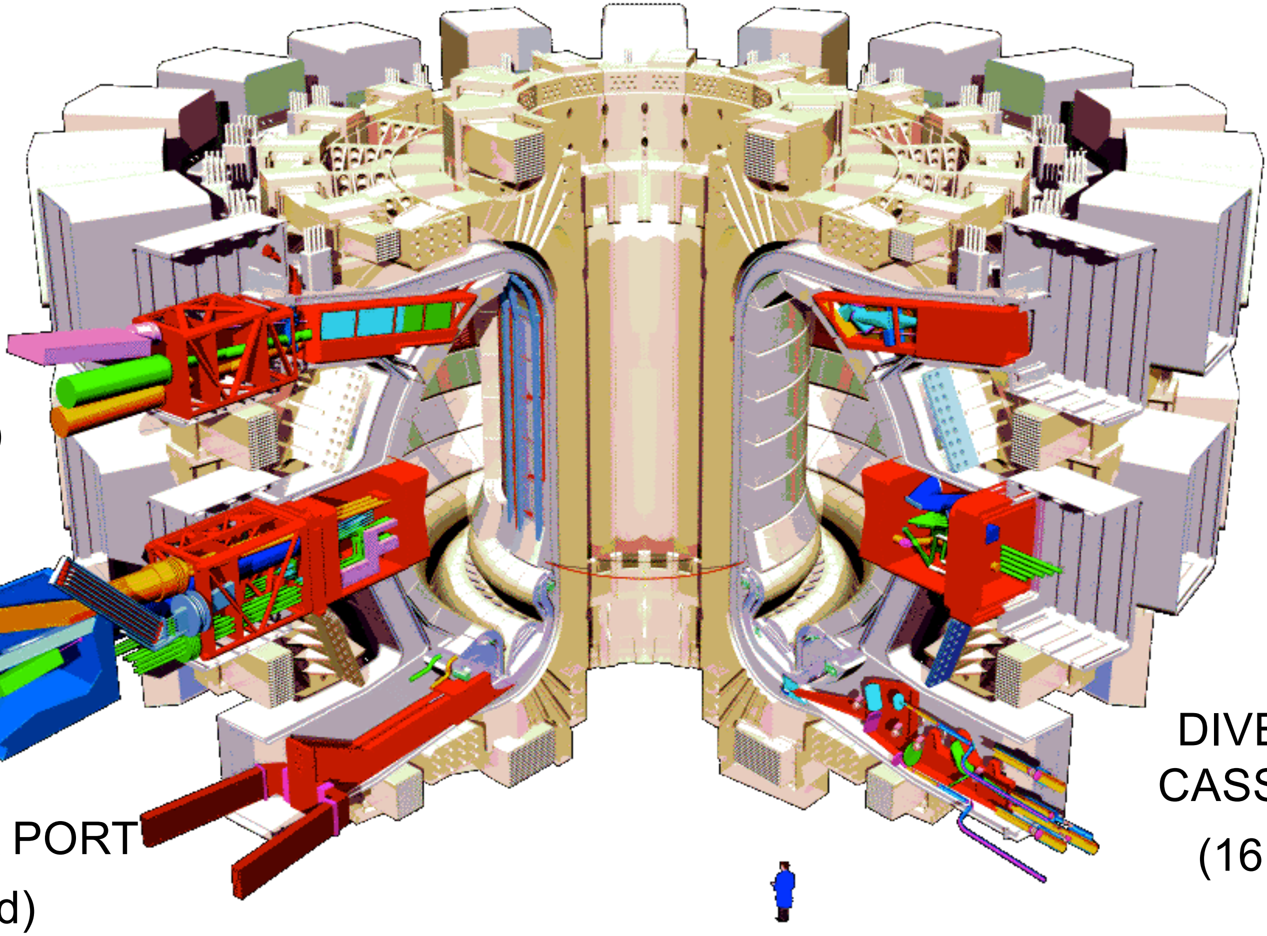
System	Power
NBI –ve ion, 1 MeV	33 MW
ECH & CD 170 GHz	20 MW
ICRH & CD 40 – 55 MHz	20 MW





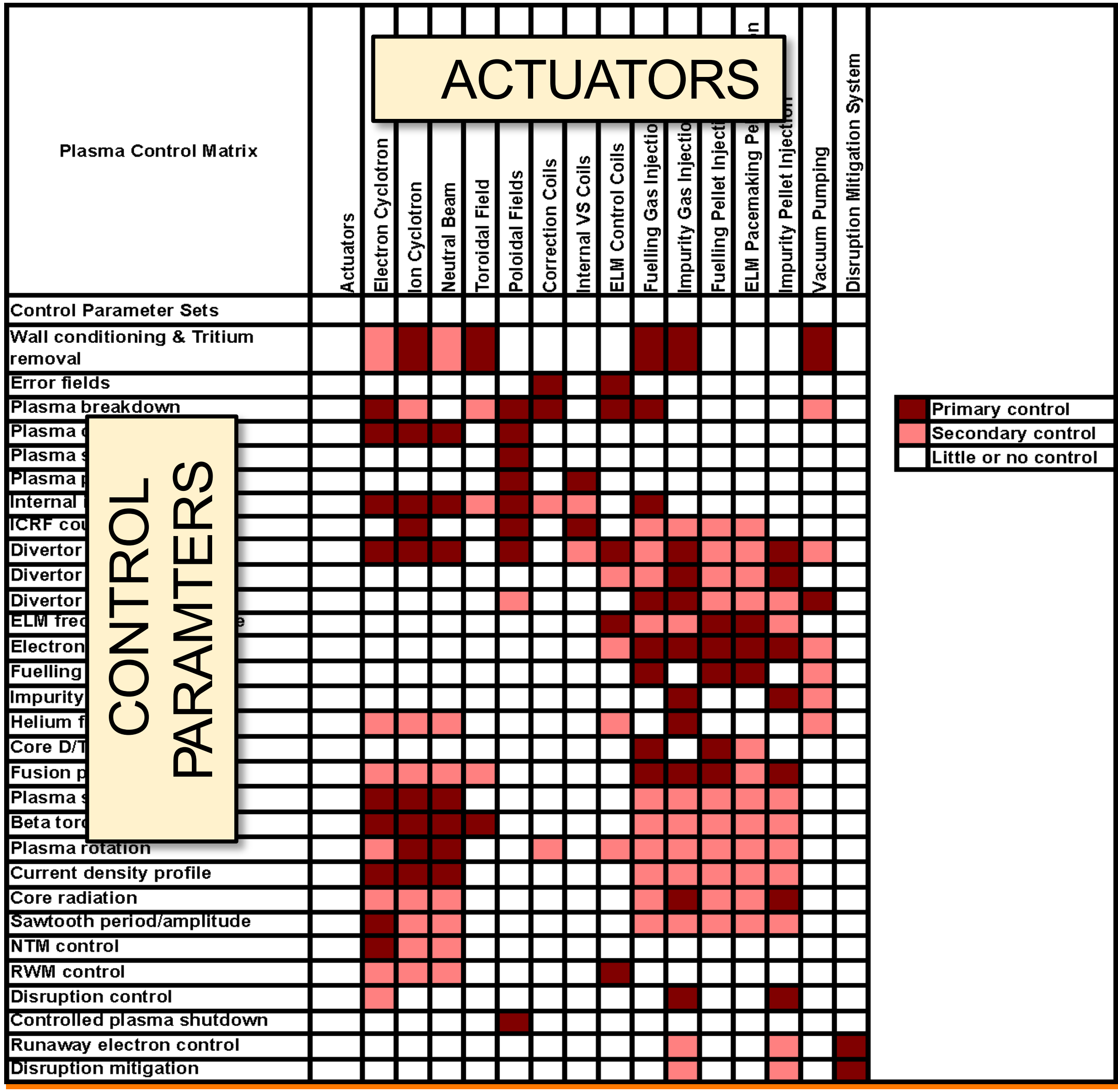
- **P_{aux} for Q_{DT} = 10 about 40-50 MW**
- **Upscale of known technology**
- **Modular for upgrades**

About 40 major diagnostic systems will be installed for machine protection, control and physics



- **Extensive control matrix, requires state-of-the-art schemes**

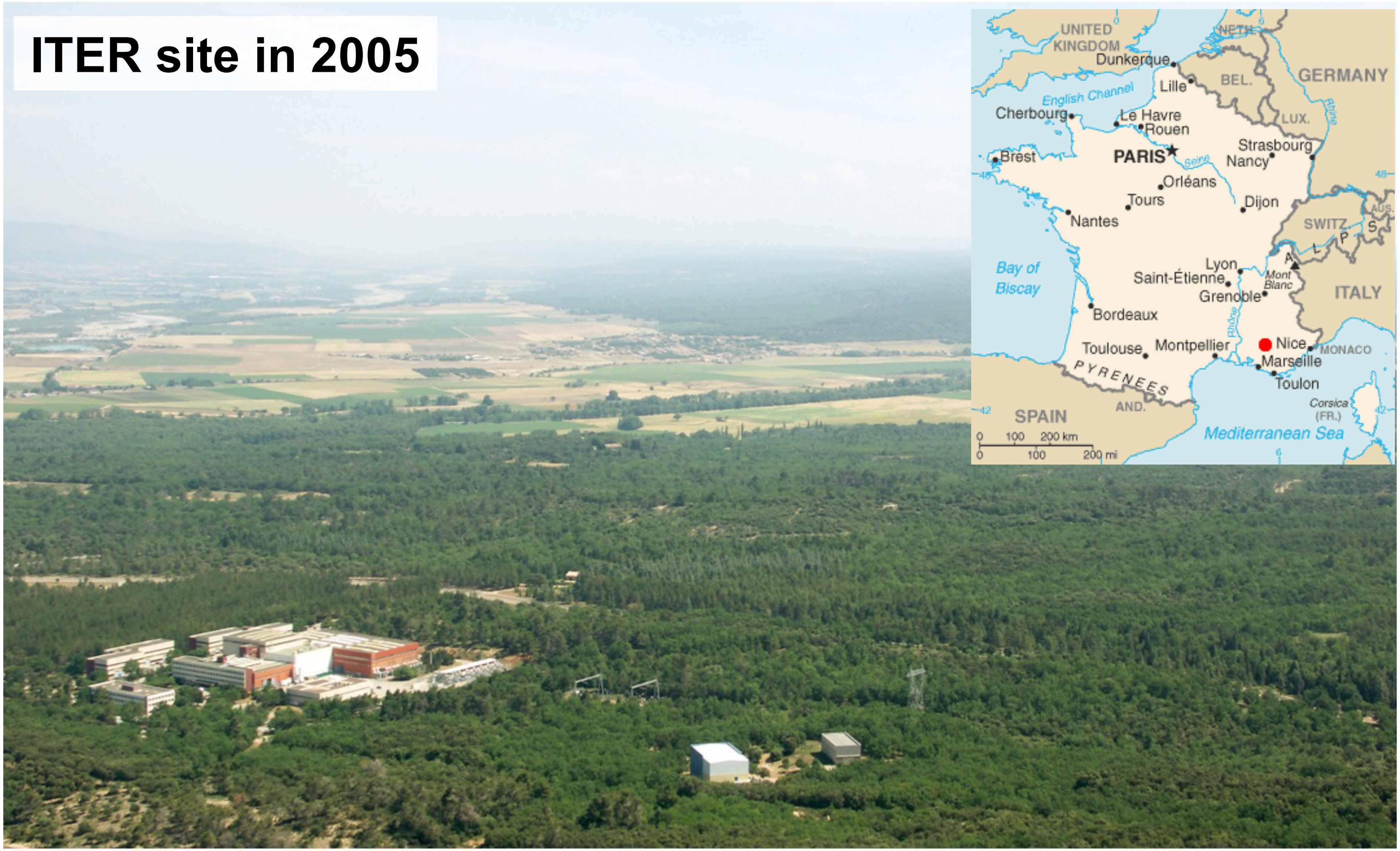
About 20 parameters will be controlled simultaneously on time scales from 1 ms to seconds



- **Extensive control matrix, requires state-of-the-art schemes**

ITER construction

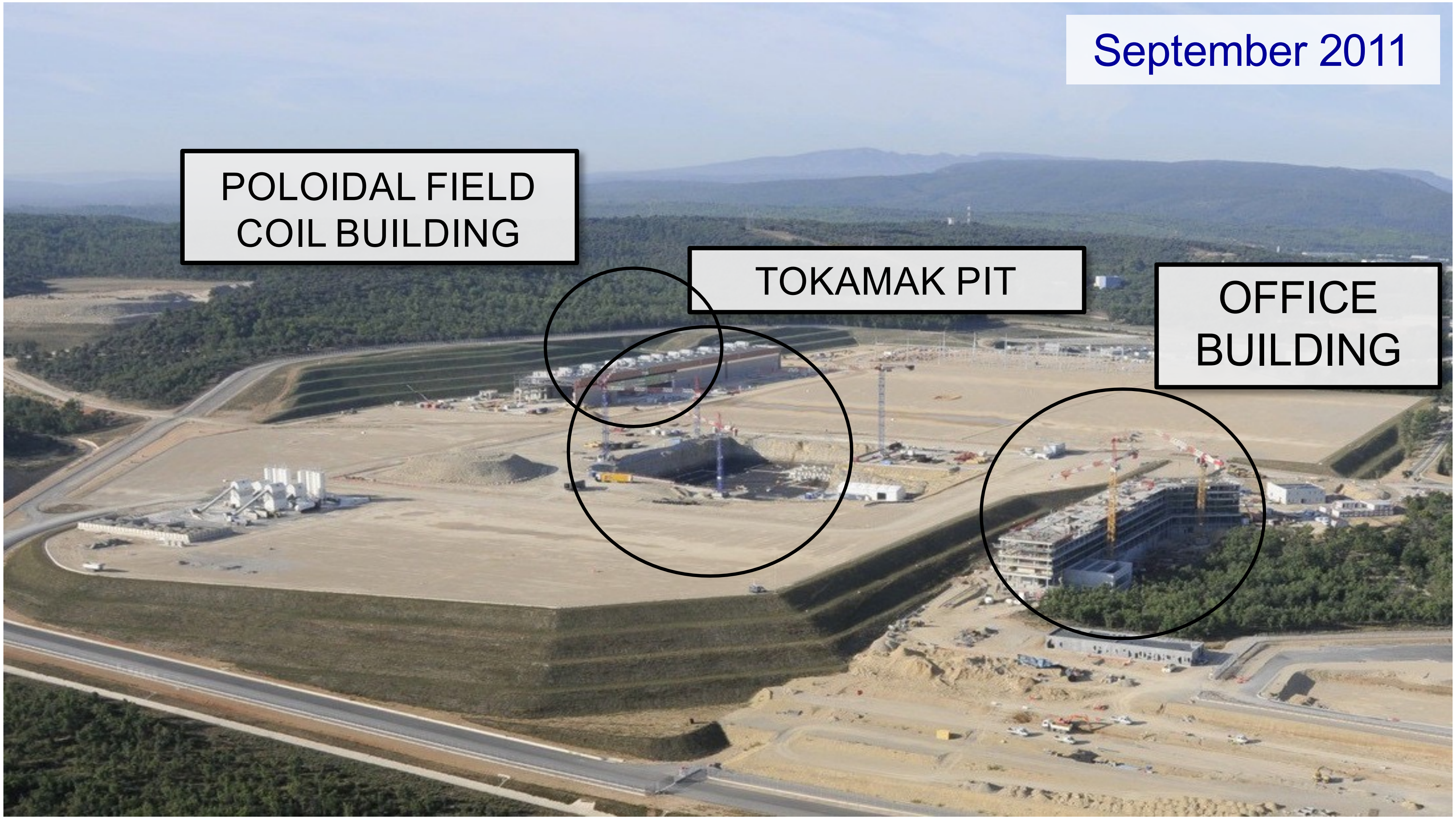
The ITER site in 2005: a woodsy area in southern France



Site preparation was finished in 2009 over a 4-year period

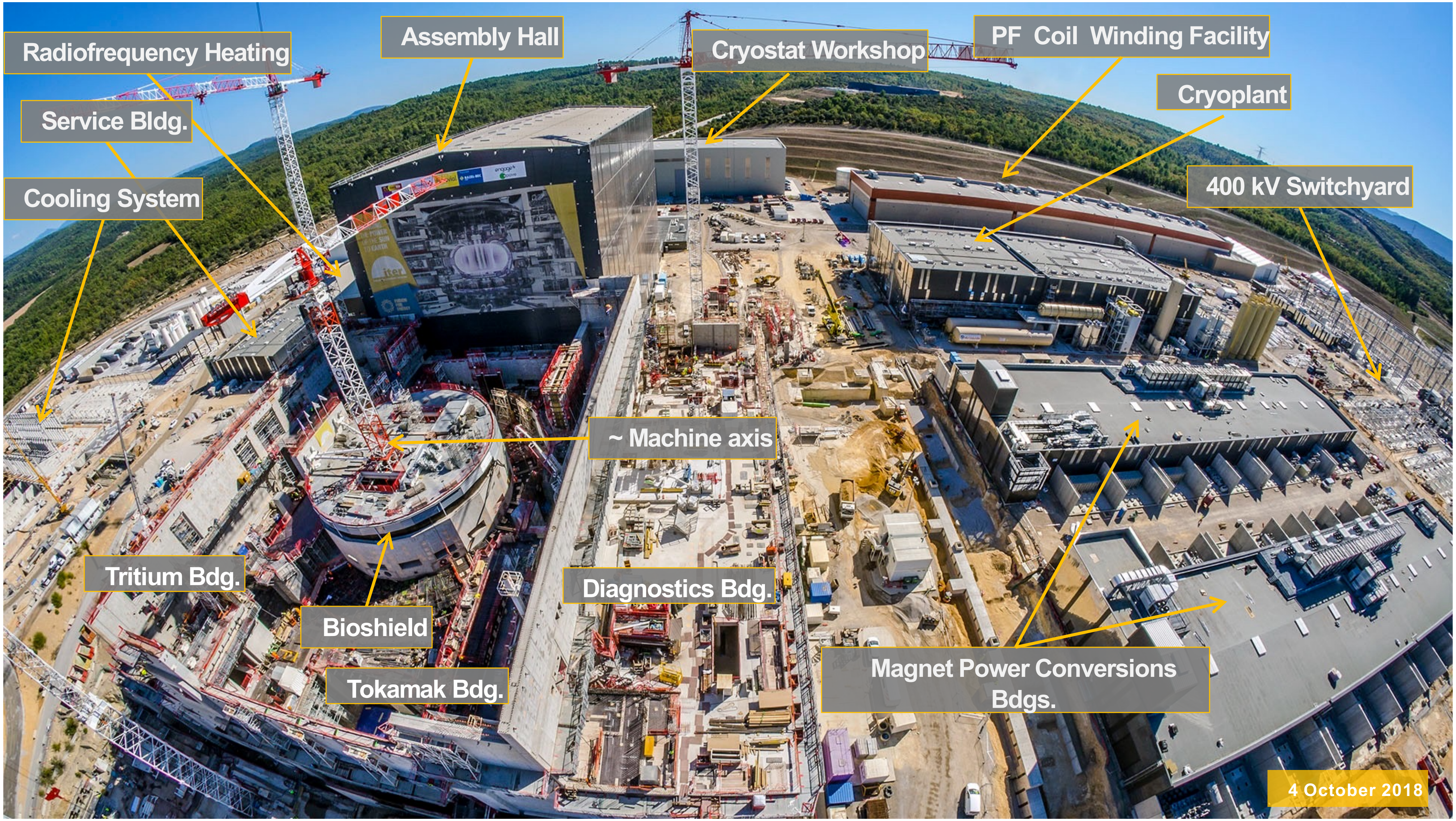
40 ha platform, 2.5 million m^3 of earth moved, good bedrock (100 t m^{-2})

The construction of the ITER buildings commenced in September 2011



Preparation of the tokamak platform was completed in September 2013

Many of the primary auxiliary buildings were completed by Oct 2018, work on the tokamak building started



The tokamak building and the assembly hall were completed by November 2020

The ITER work site in October 2021

The ITER work site in April 2022

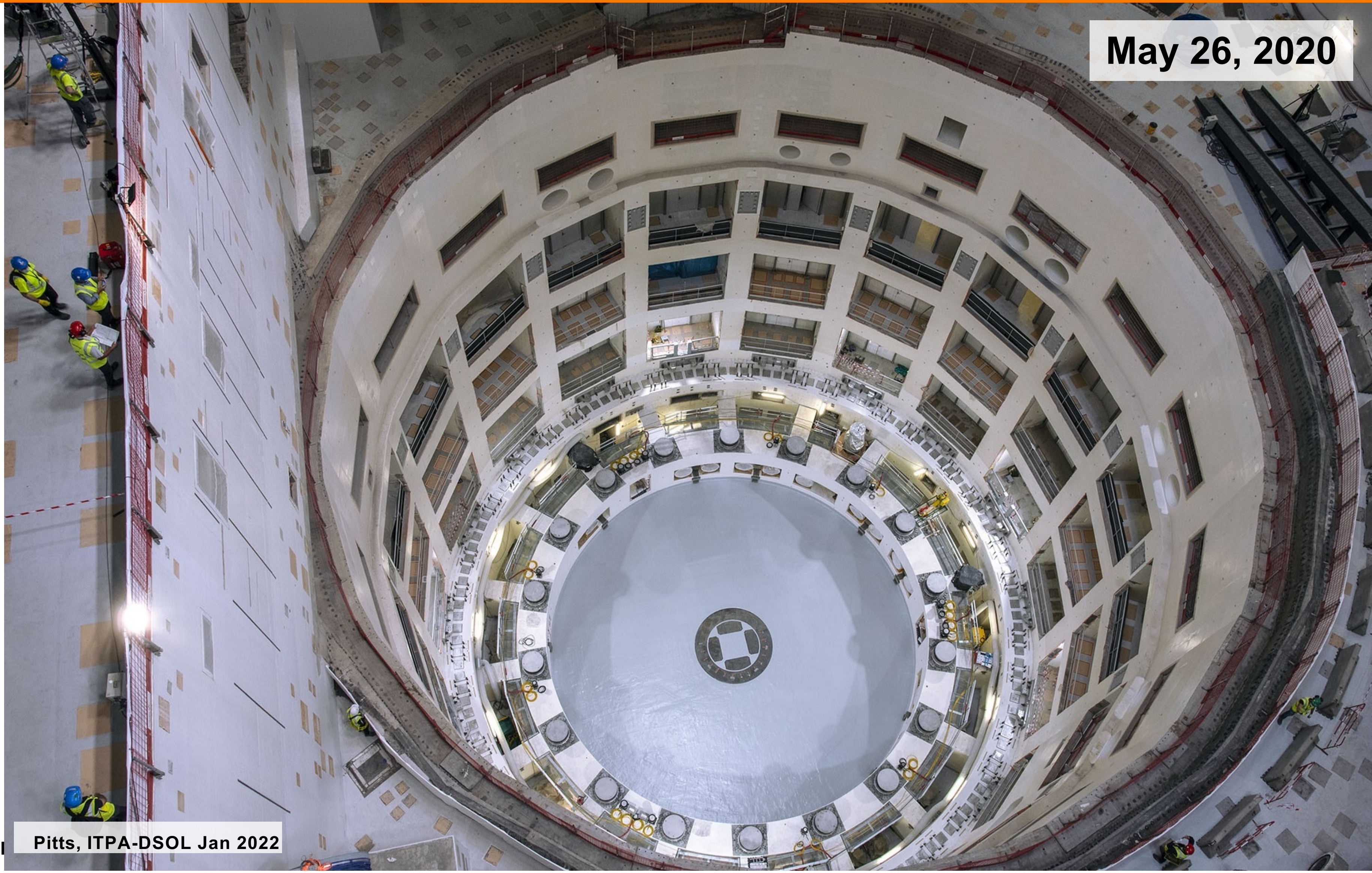
In December 2022, more than 80% of the civil work is completed

Luce, Fusion Power Associates, Dec 2021

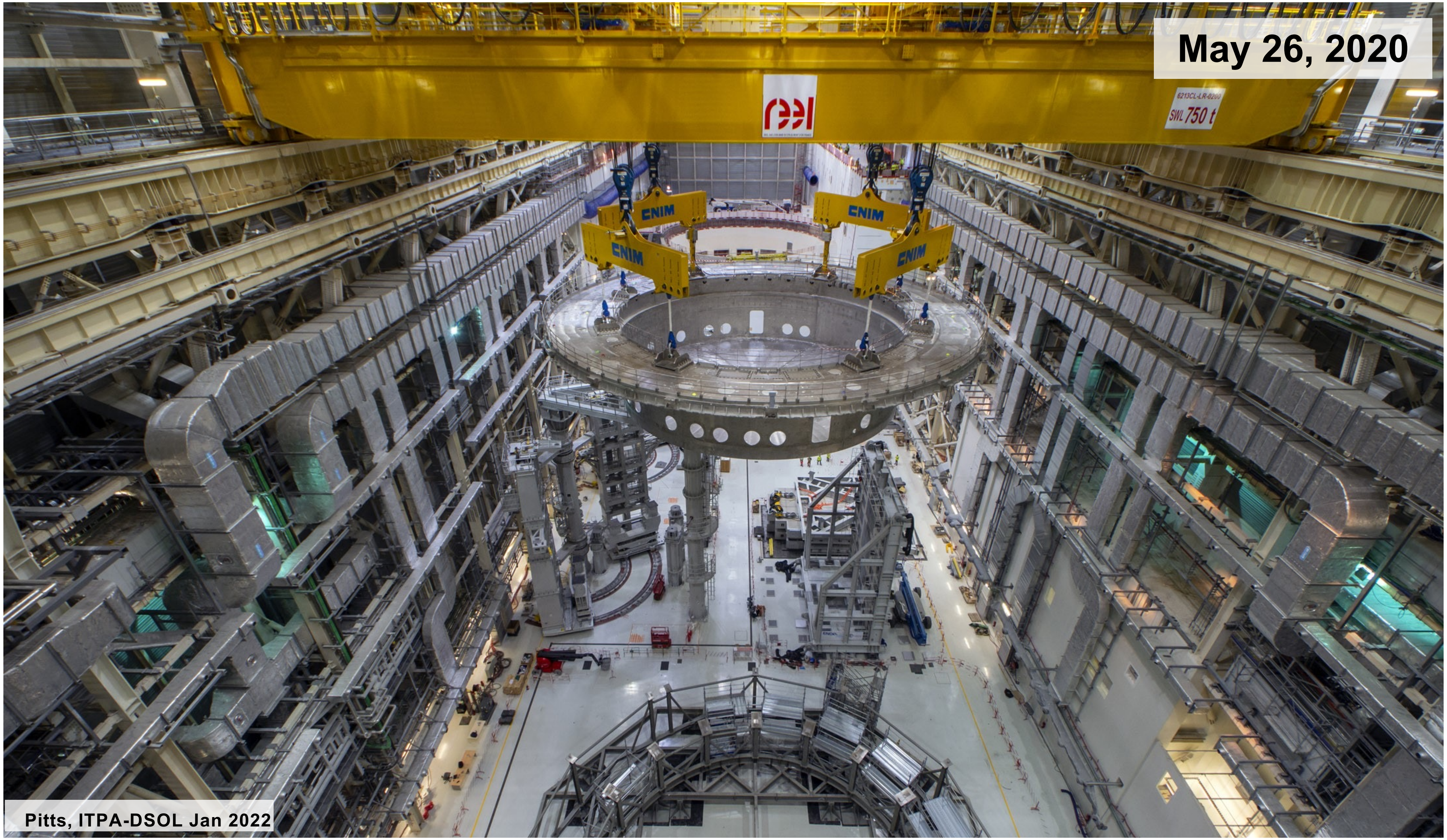
Homework assignment

Watch drone fly-overs on
https://vimeo.com/255049451/3aa0a0616d

Temporary bioshield lid removed: tokamak pit painted up and ready for first major components

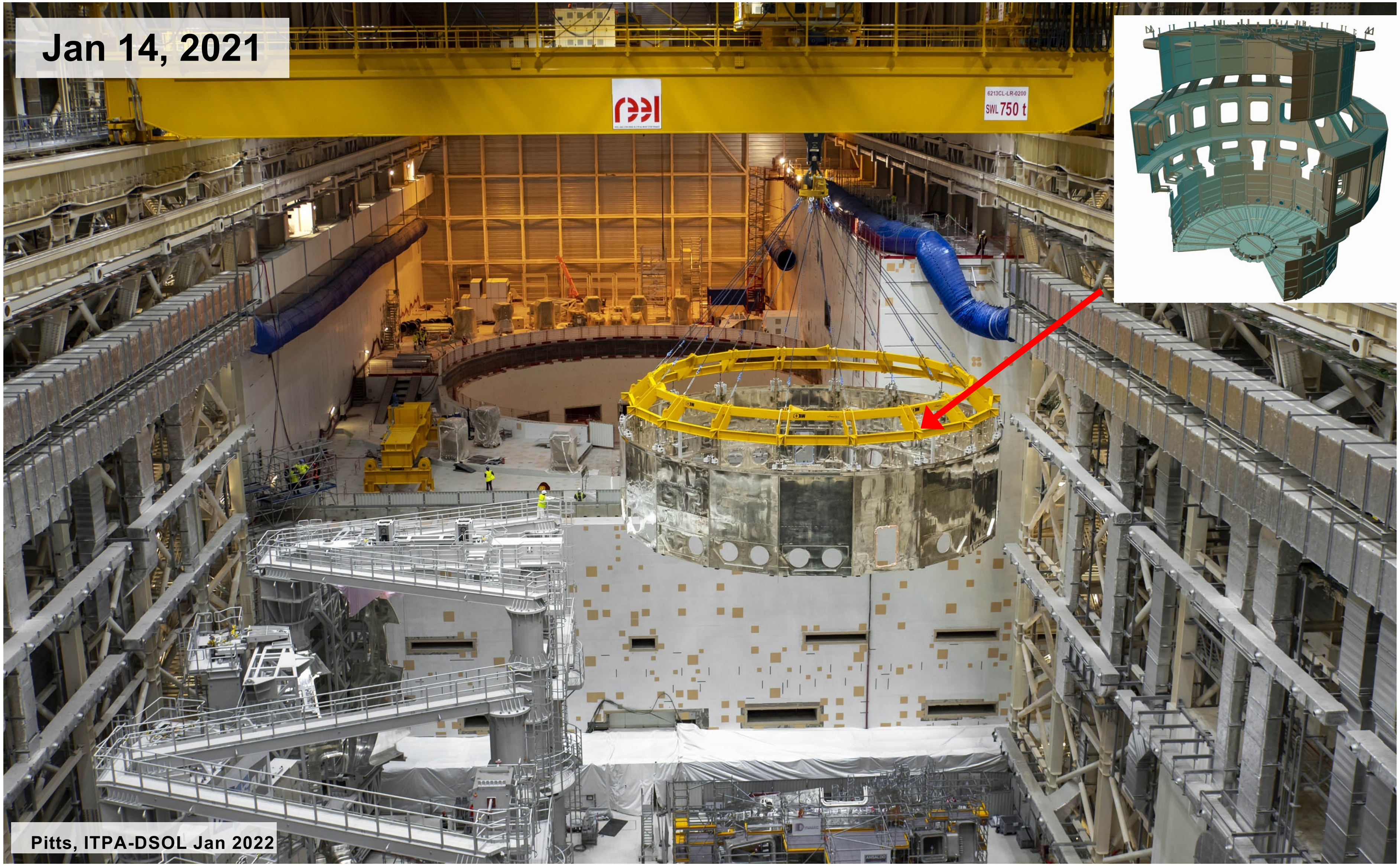


The big lift: 1250-t, 30-m diameter cryostat base on its way to the pit

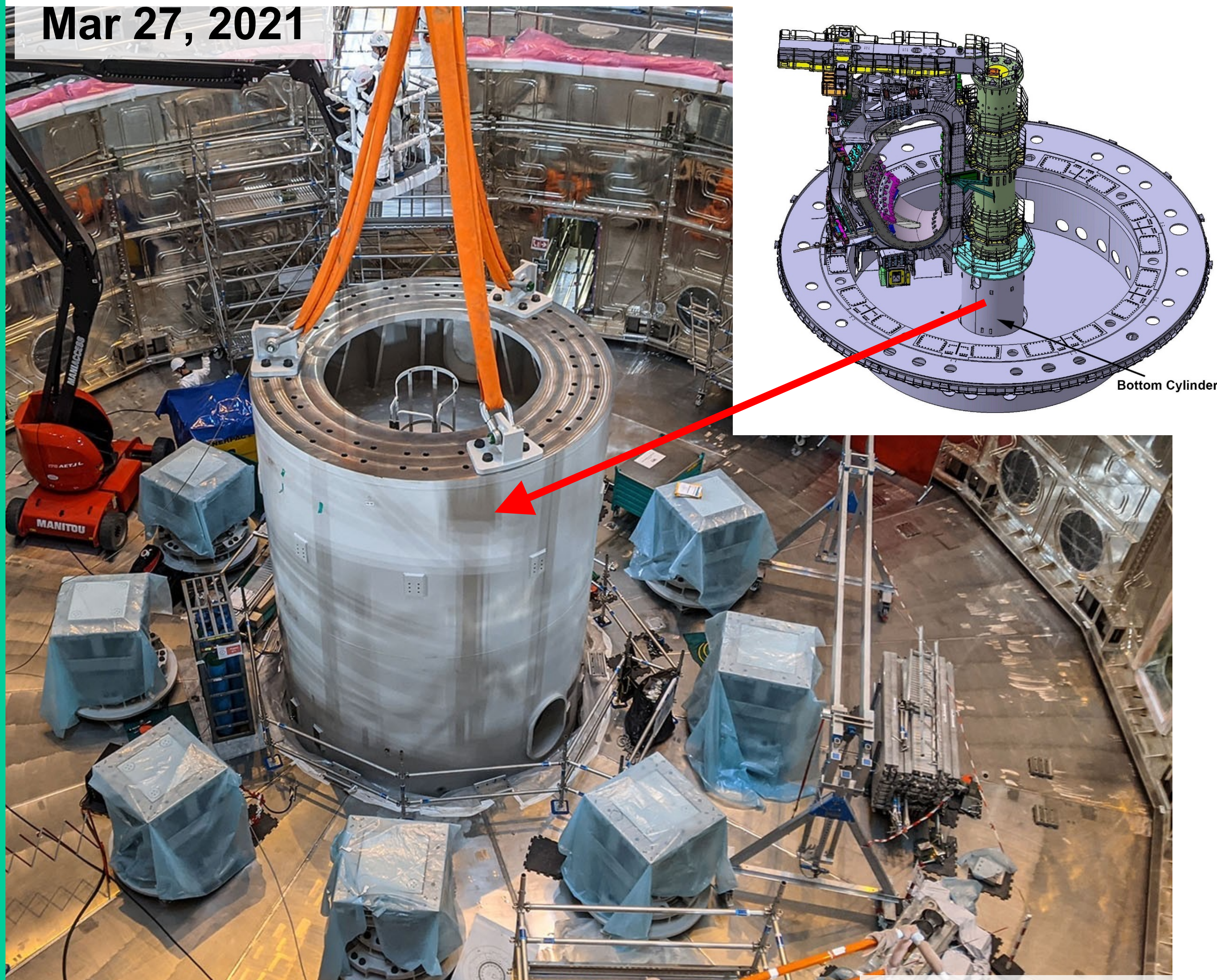


375-t cryostat cylinder is lowered into the pit

Lower cylinder thermal shield on its way

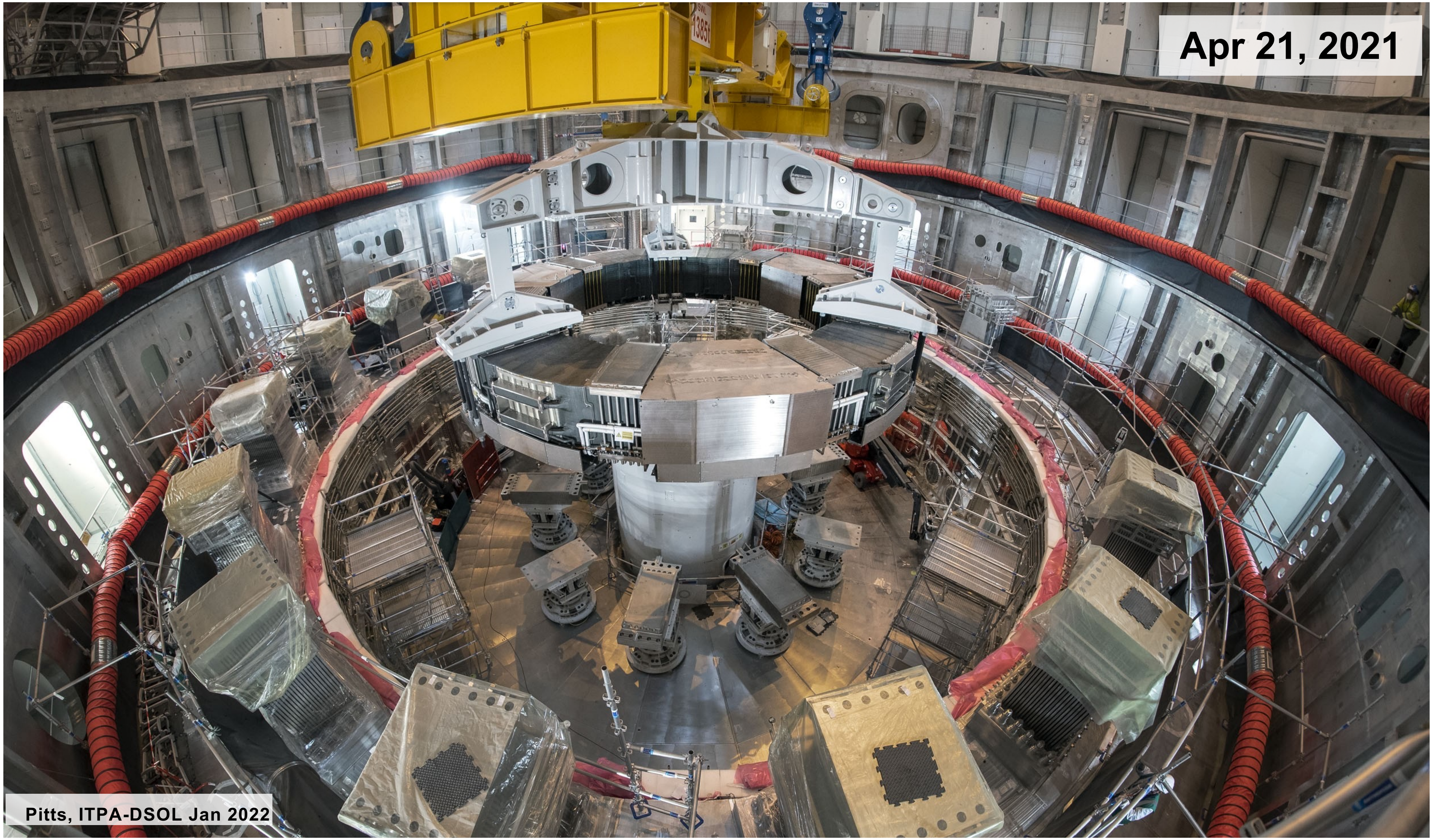


Lower cylinder of the in-pit assembly tool is installed

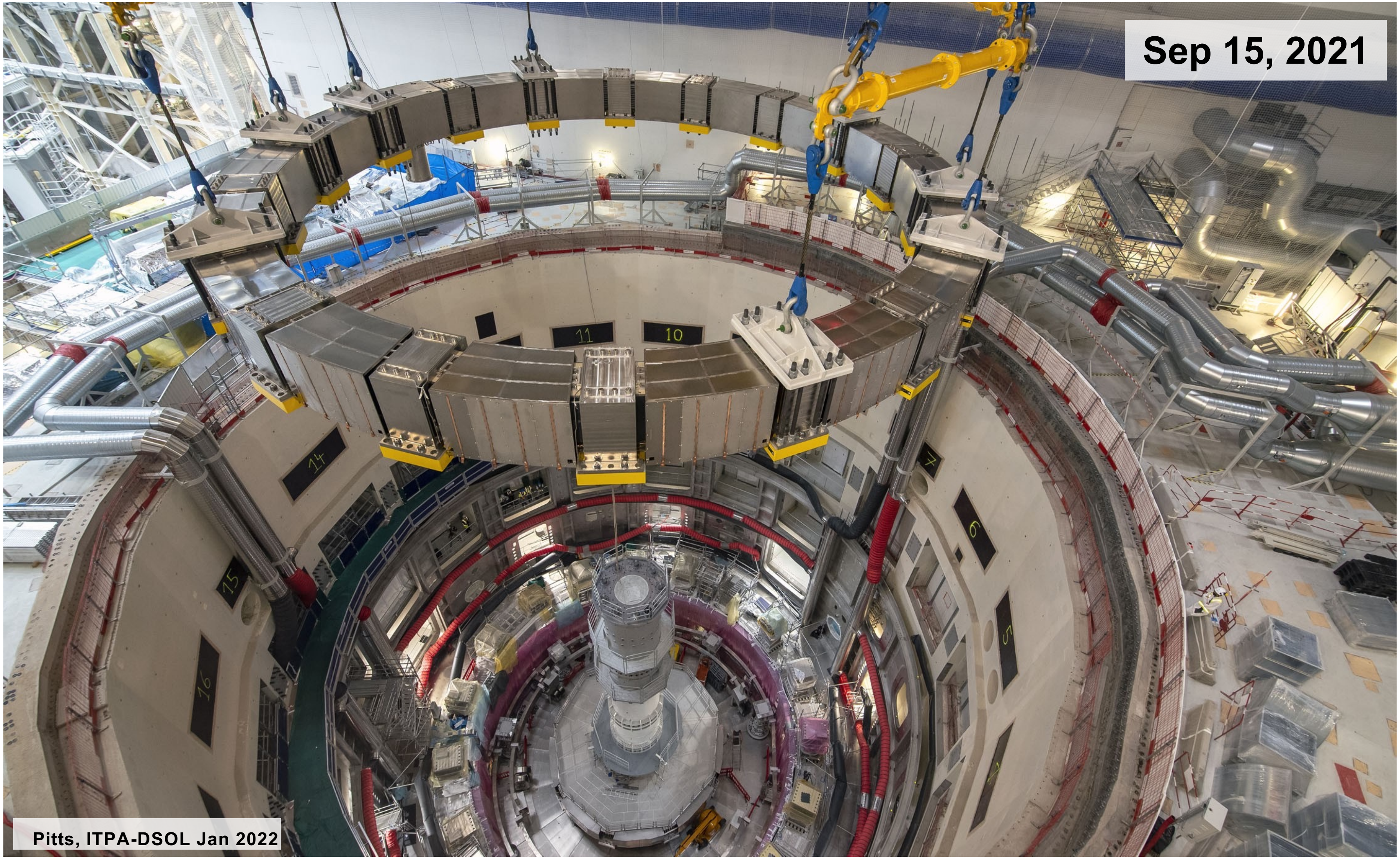


Pitts, ITPA-DSOL Jan 2022

First poloidal field coil (PF6) is inserted onto temporary supports

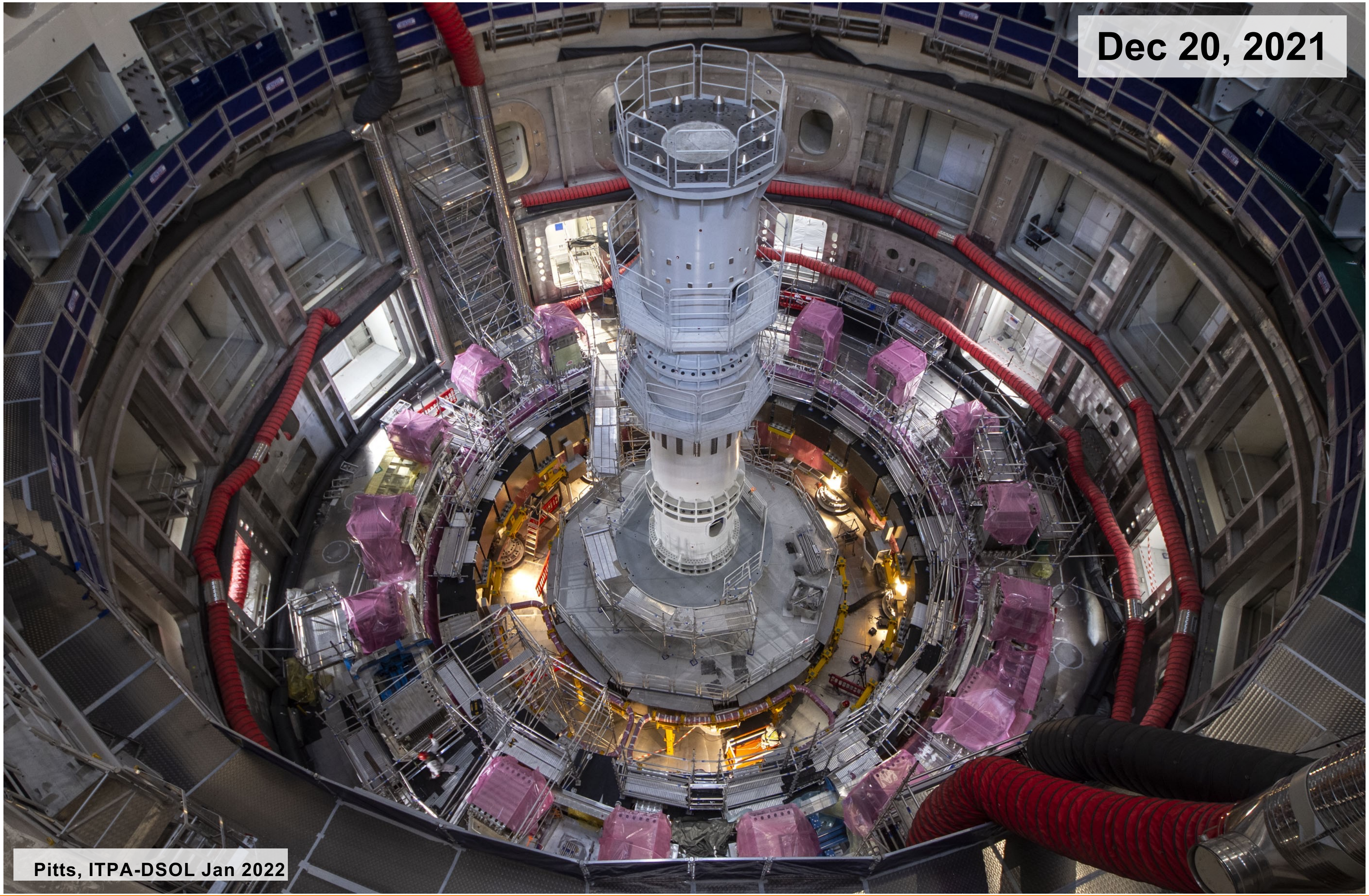


Poloidal field coil no. 5 is lifted into the tokamak pit

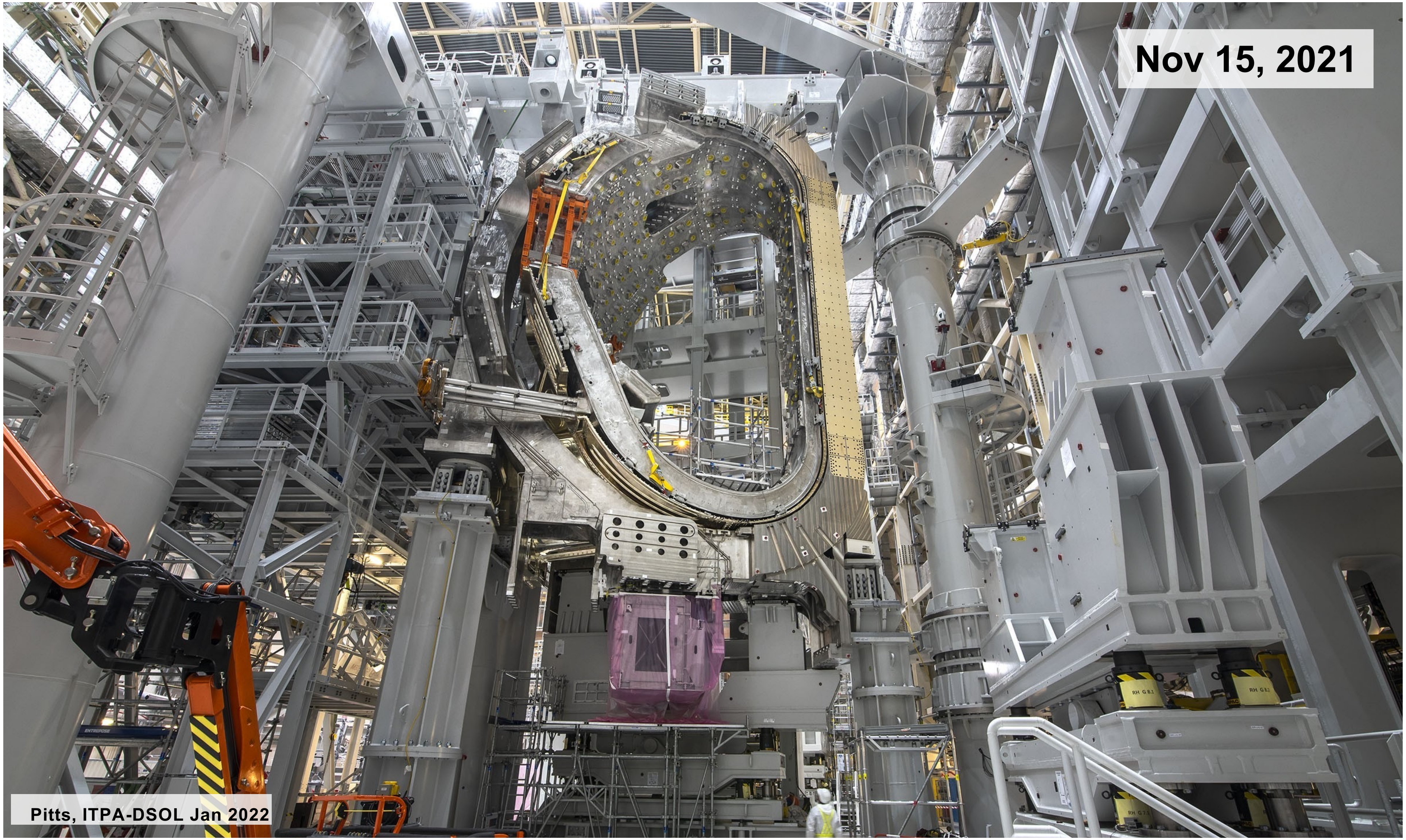


Metrology and adjustment of PF5 and PF6 are performed

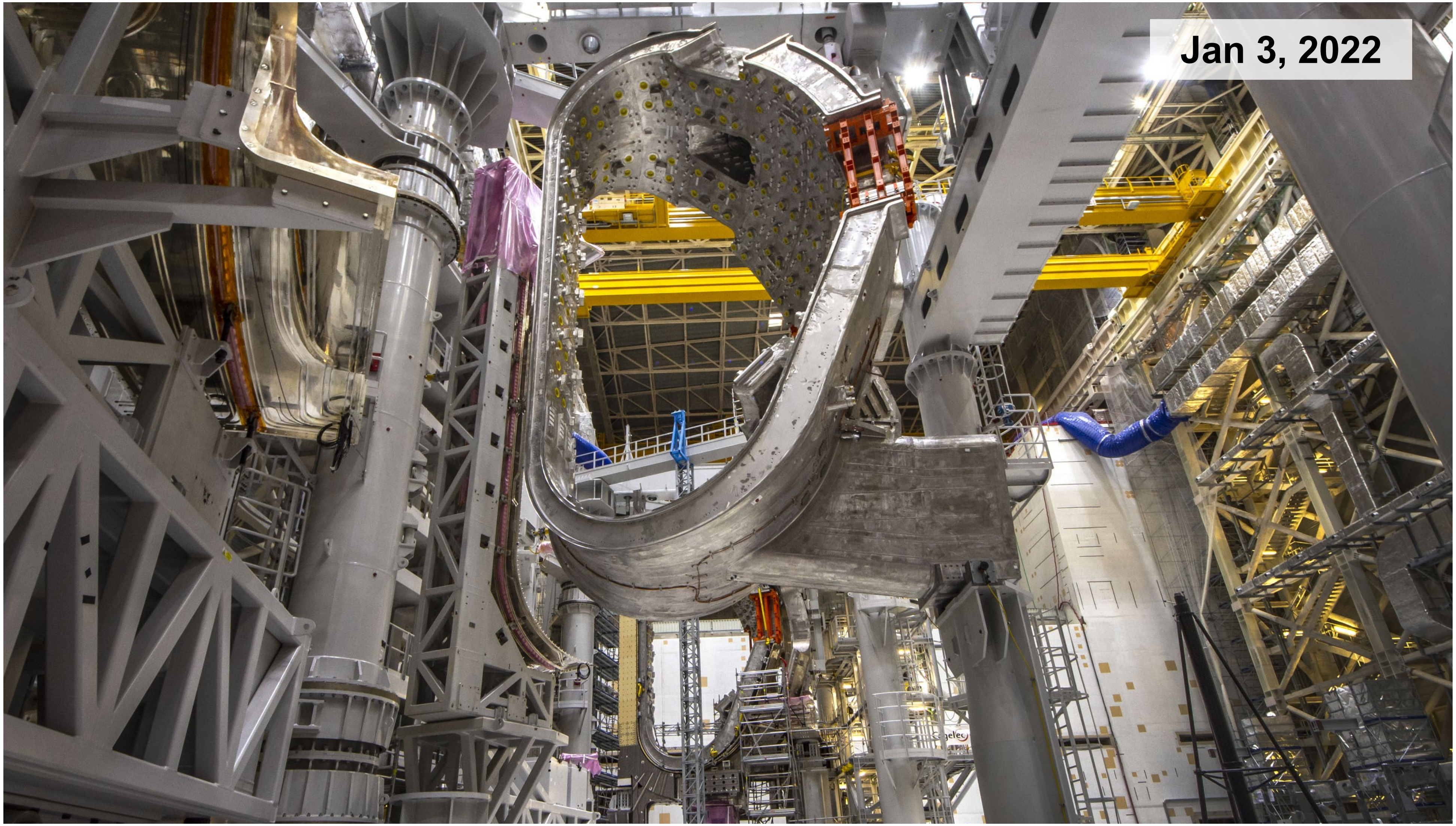
Tokamak Pit ready for the first vacuum sector



Meanwhile in the assembly hall … first complete vacuum vessel sector (6) ready for pit installation

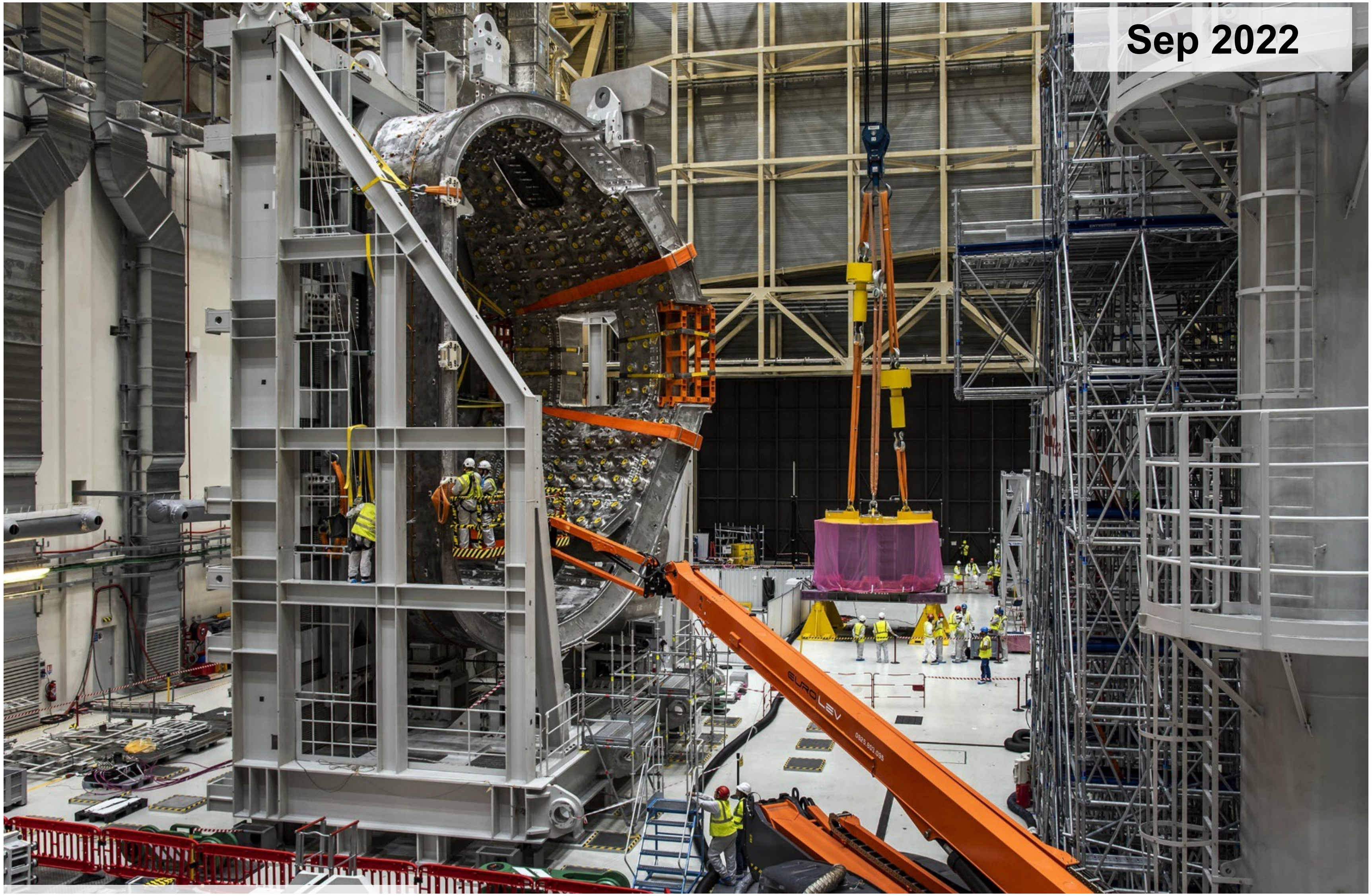


VV Sectors 6 and 7 both on sector-sub assembly tool (SSAT) tools



Pitts, ITPA-DSOL Jan 2022

The third sector subassembly was put together in September 2022



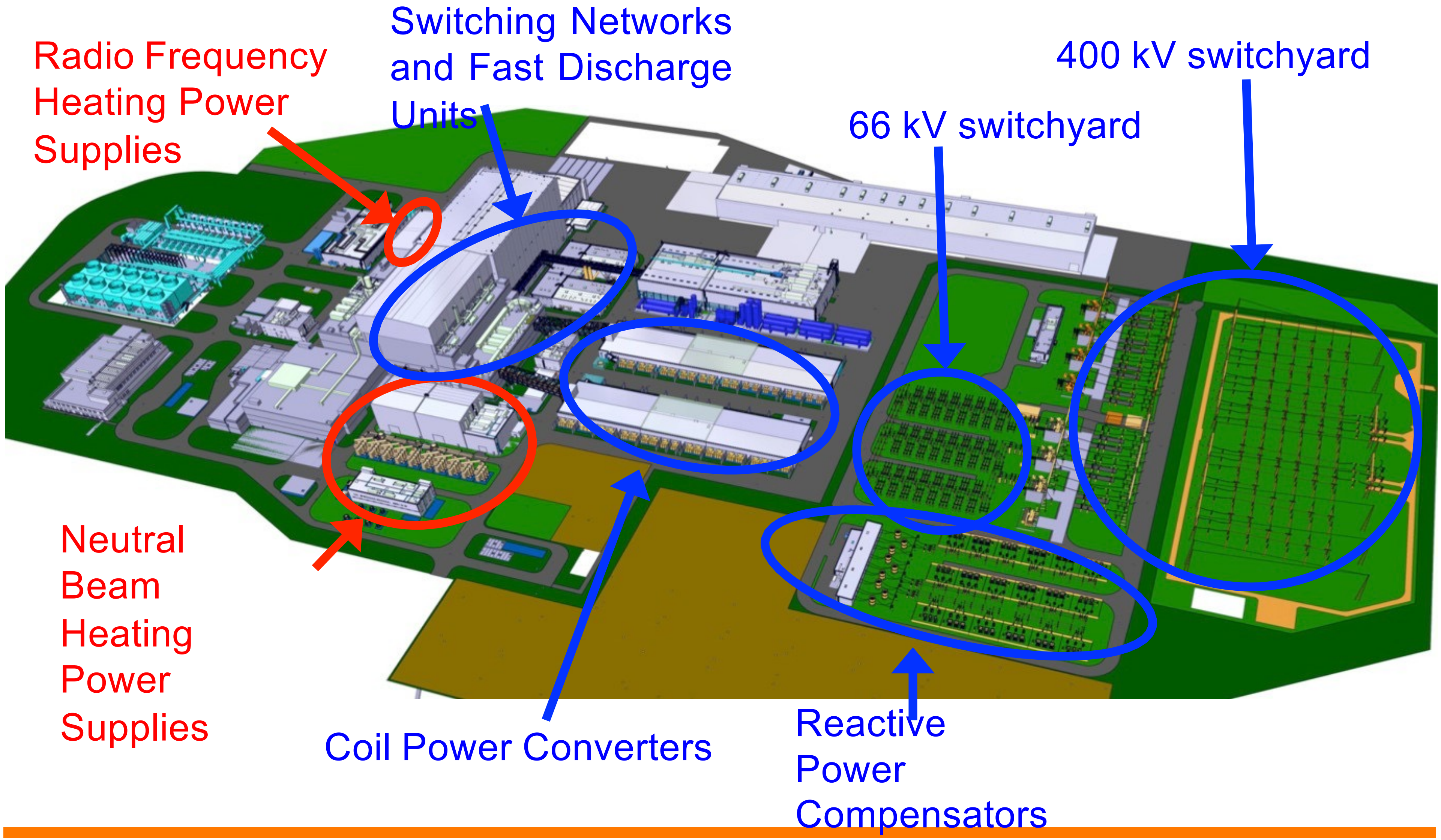
Becoulet, Fusion Power Associates Dec 2022

Homework assignment

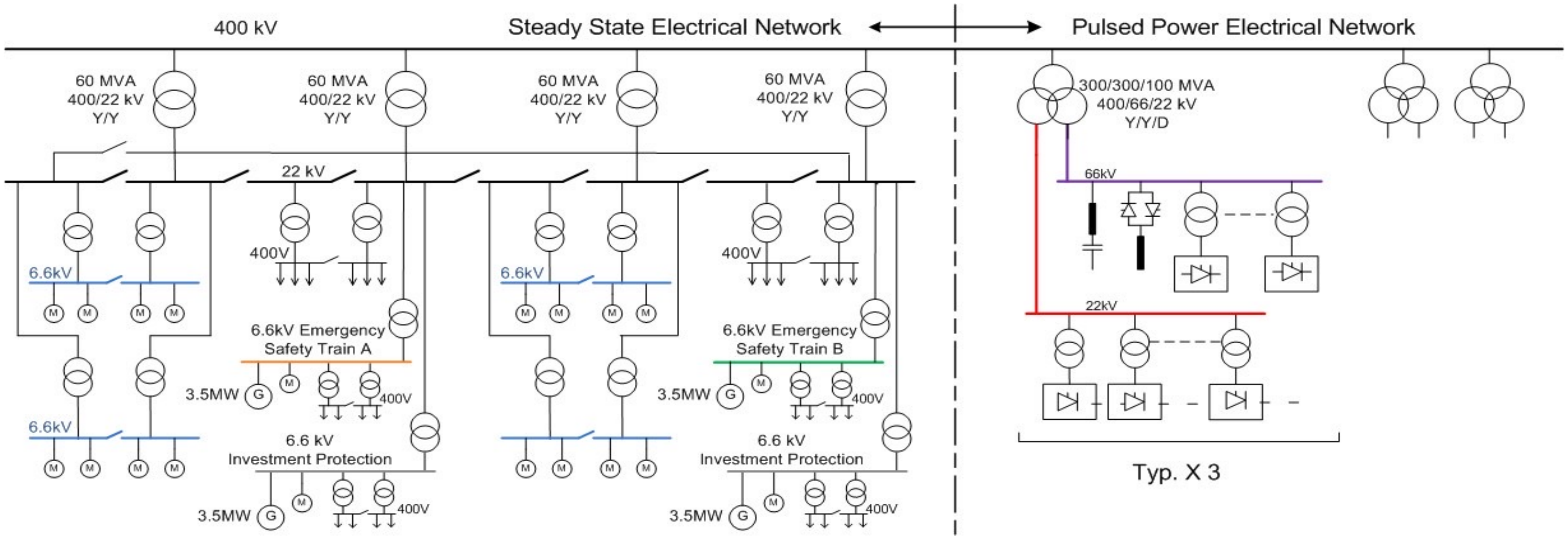
Assembly of ITER: https://www.iter.org/news/videos/611

Other site developments and considerations

The 400 kV (and 66 kV) switch yards serve the tokamak and auxiliary heating systems



The pulsed electrical network can deliver about 500 MW peak pulse



Steady State Electrical Network

about 120 MW continuous power

Main consumers:

- Cooling Water System
- Cryoplant
- Building services

Pulsed Power Electrical Network

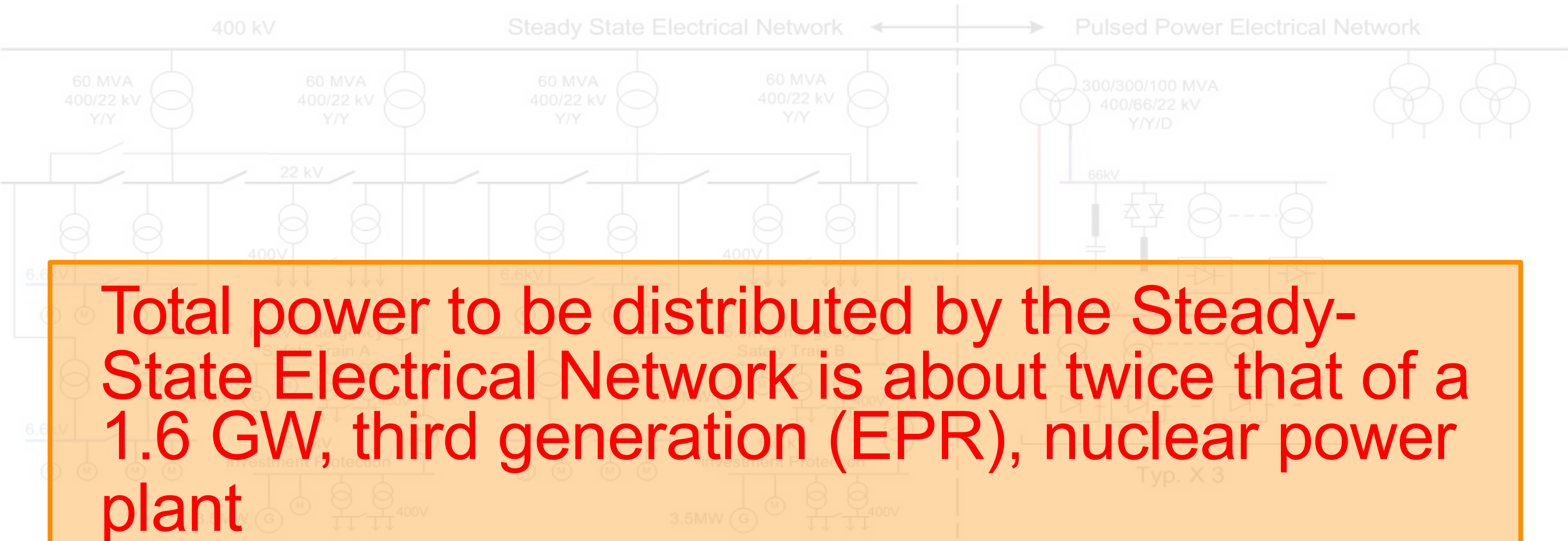
about 500 MW peak pulse

Main consumers:

- Coil power converters
- Radio Freq. and Neutral Beam systems

Includes large Static Var Compensators

The pulsed electrical network can deliver about 500 MW peak pulse



Total power to be distributed by the Steady-State Electrical Network is about twice that of a 1.6 GW, third generation (EPR), nuclear power plant

Steady State Electrical Network

about 120 MW continuous power

Main consumers:

- Cooling Water System
- Cryoplant
- Building services

Pulsed Power Electrical Network

about 500 MW peak pulse

Main consumers:

- Coil power converters
- Radio Freq. and Neutral Beam systems

Includes large Static Var Compensators

Large components arriving in France must be transported ~100 km from the Mediterranean coast to ITER site

Road upgrades from south coast to Cadarache complete and paid for by regional funding (115 M€)

Arrivals of major components from offsite laboratories and factories to the ITER site in 2020

Bigot, Fusion Power Associates, Dec 2020

Deliveries of vacuum vessel sectors and central solenoid coils in 2022

Three VV sectors delivered (Republic of Korea)

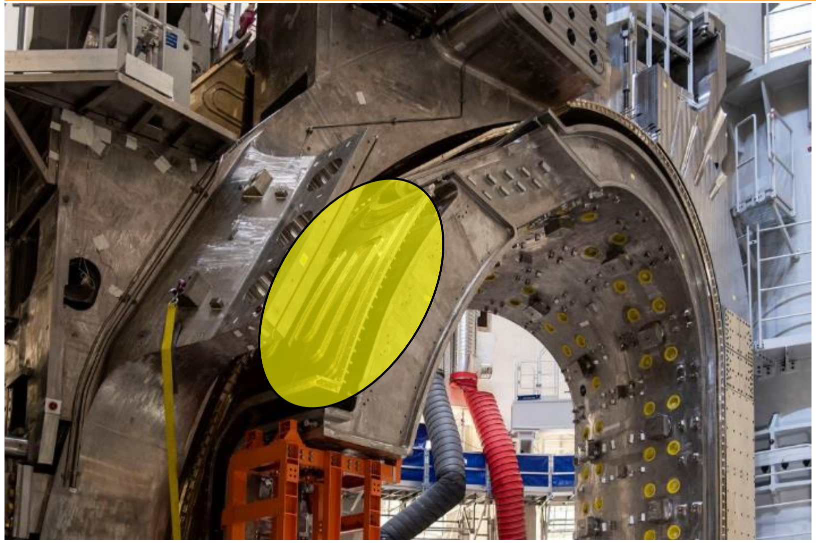
Two central solenoid modules delivered, five more in late stages of fabrication (US)

Becoulet, Fusion Power Associates Dec 2022

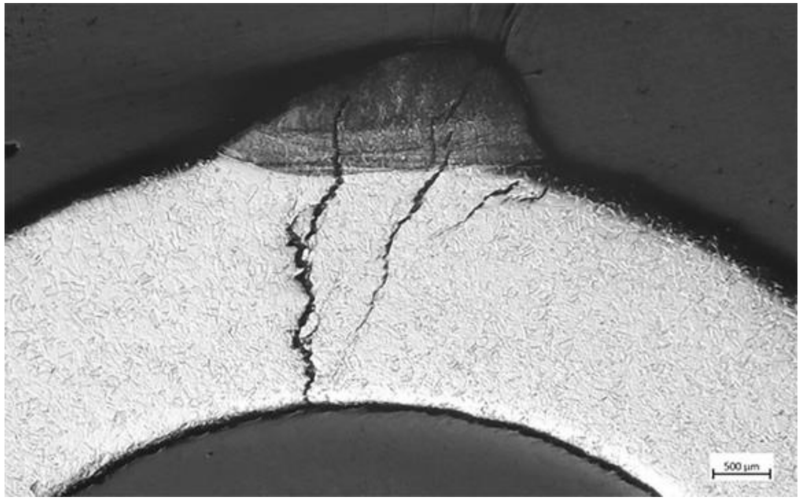
Poloidal field coil #1 in shipment in St. Petersburg, Russia, in October 2022

Becoulet, Fusion Power Associates Dec 2022

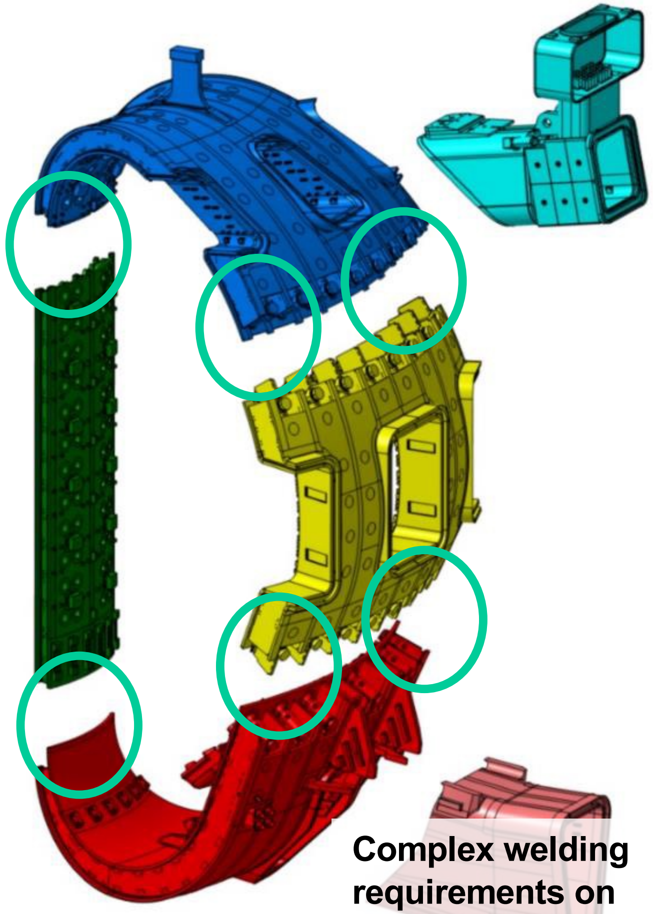
Several design and assembly issues encountered in 2022 slowing down progress of assembly



Thermal shield: actively-cooled component between the VV sectors and the TF coils



Cracks detached in the thermal shield cooling pipes caused by stress corrosion due to chlorine residues (design flaw) ⇒ replace of pipes



Complex welding requirements on the four main sections of the VV sectors causing deviations

Becoulet, Fusion Power Associates Dec 2022

Summary

- **ITER is a multi-national collaboration to construct the first burning-plasma fusion reactor based on the tokamak concept**
  - Significant challenges in physics and technology, and the integration of both, nuclear licensing of project
- **Construction of buildings and components (off-site) commenced in 2009 ⇒ by November 2020, >80% of the civil engineering work on the ITER site was completed**
- **First parts of the cryo-stat, vacuum vessel, PF and TF coils and thermal shields are currently assembled and installed in the pit**
- **ITER schedule for the first plasma (non-nuclear, hydrogen or helium) currently being assessed, likely not in 2025**

Presemo quiz #2

https://presemo.aalto.fi/fet/