(Status of) The ITER project

Prof. Dr. Mathias Groth
Aalto University
School of Science, Department of Applied Physics

Aalto University
School of Science

Outline

- **What is ITER? ⇒ main physics and technology goals**
- **Status of the site**
- **Device dimensions and operational regimes**
- **Design of key components**

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

- **Partners:** EU (+ Switzerland), 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), 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 techn… …eful 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

ITER's project challenges are significant

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

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

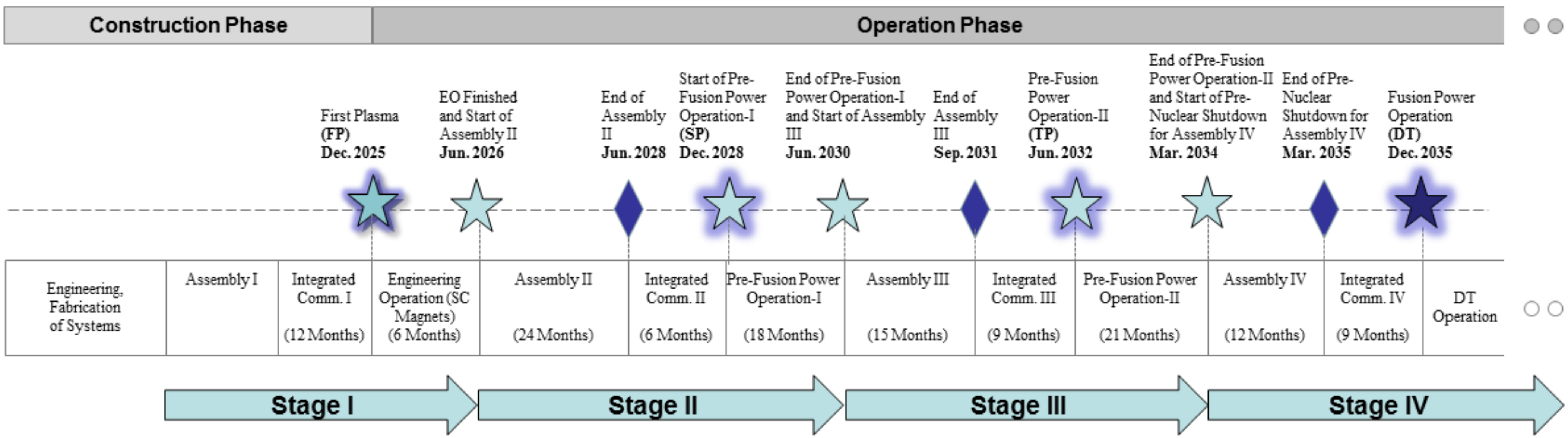
$\Rightarrow$

Essential step toward DEMO

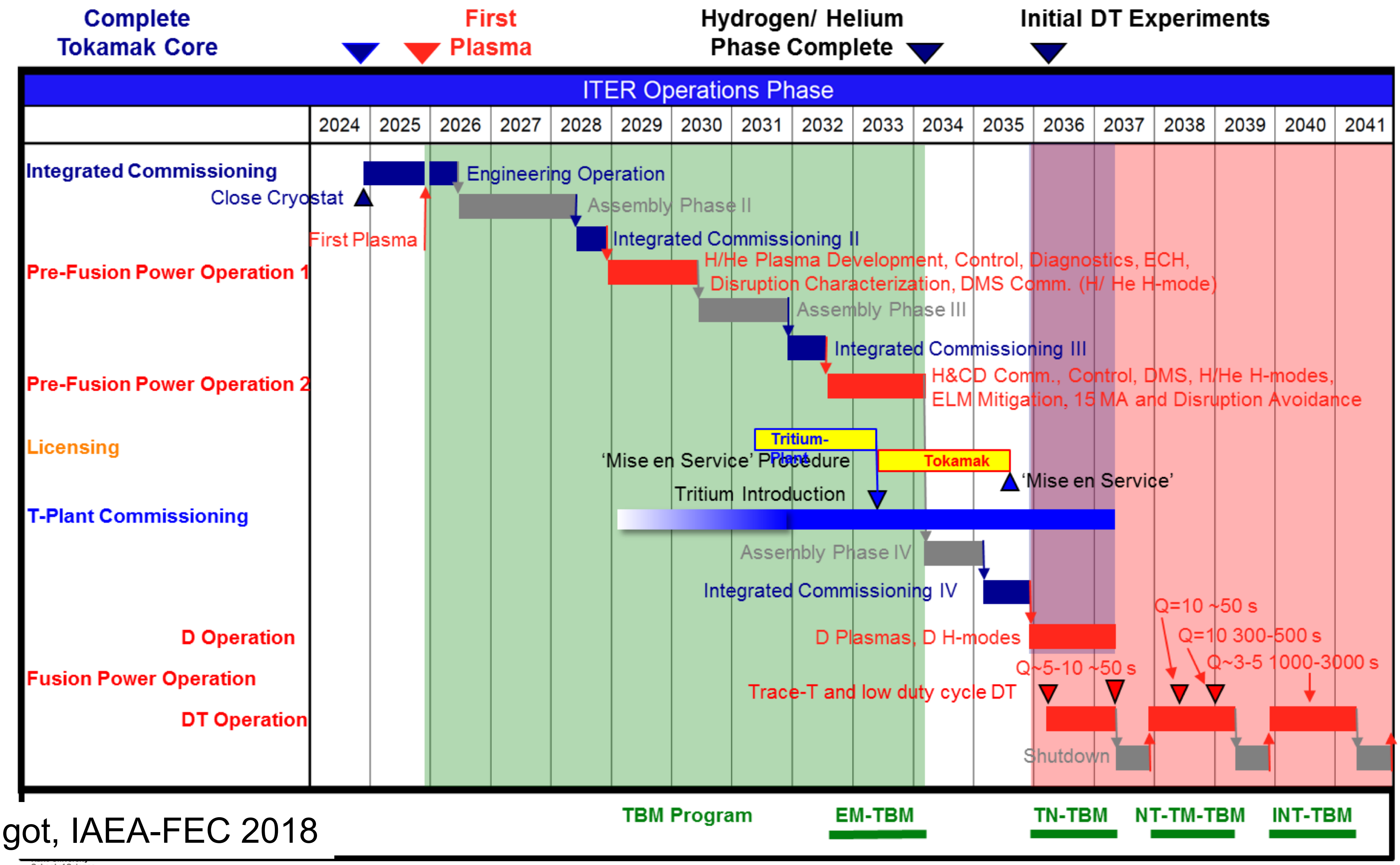
(or demonstration that tokamaks do not work)

A revised version in 2016 put the start of ITER operation in December 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**



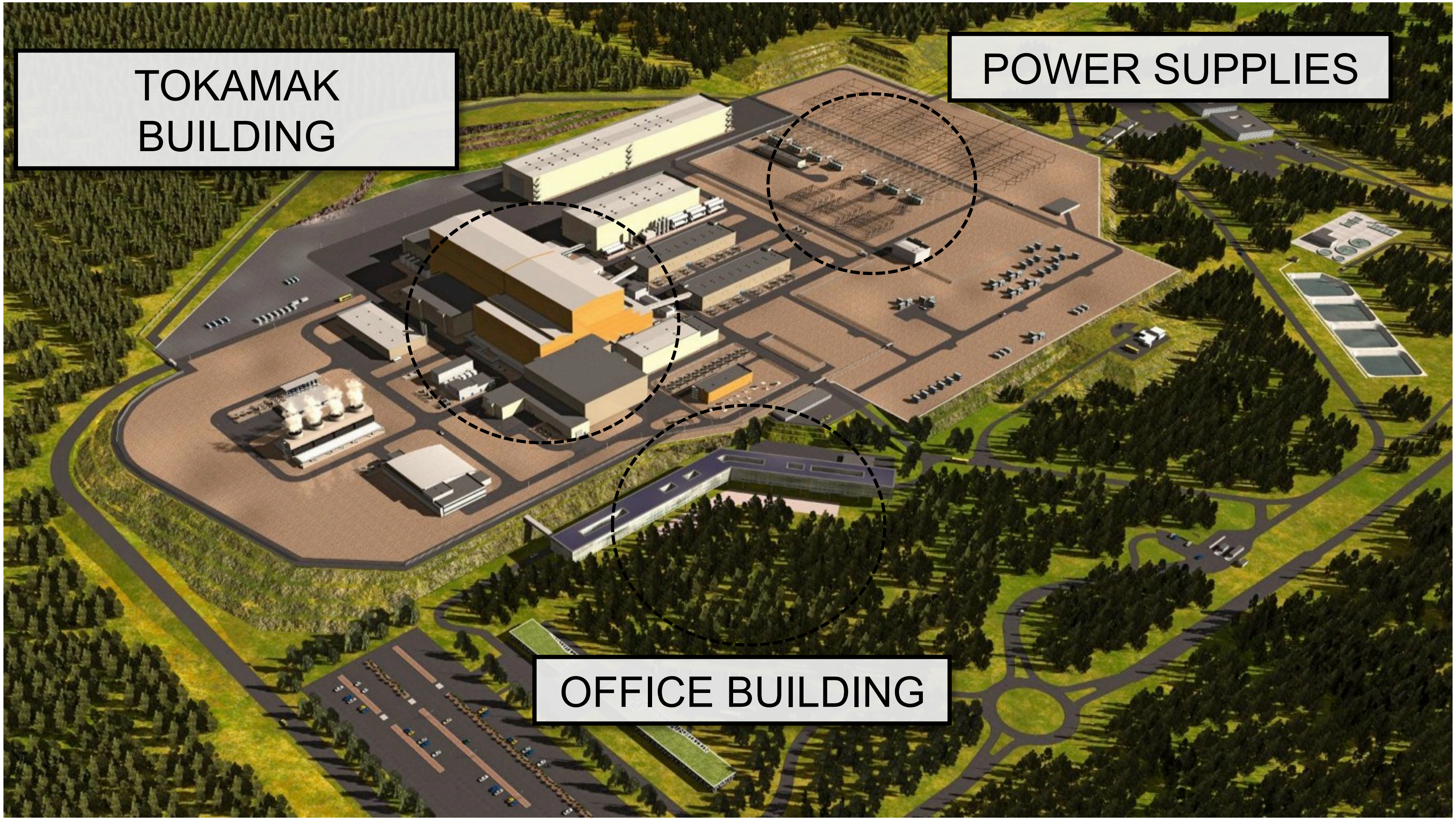
A revised version in 2016 put the start of ITER operation in December 2025, first DT ops in 2036



Bigot, IAEA-FEC 2018

School of Science

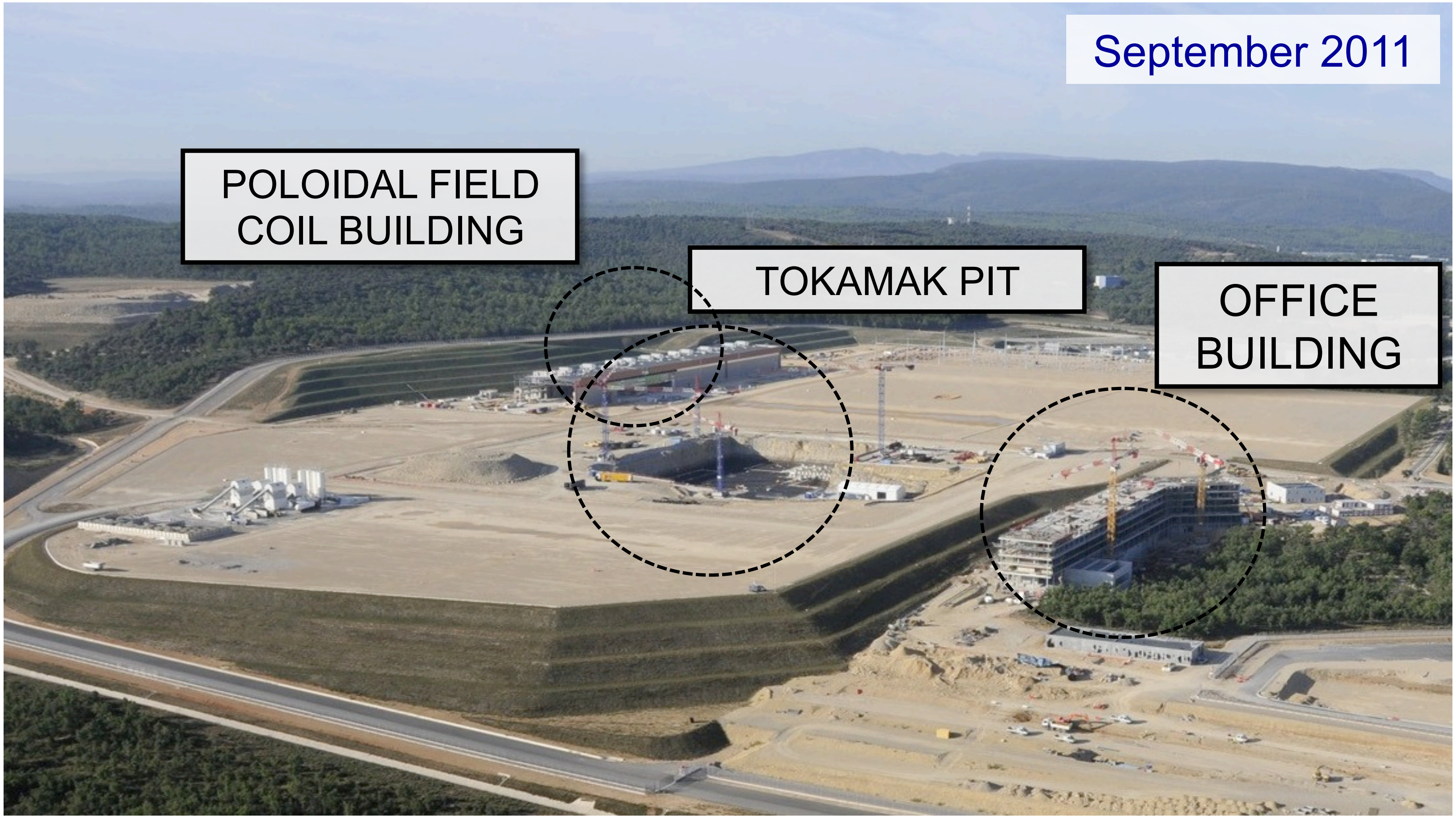
The ITER site includes a total of 39 buildings on 180 hectares



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

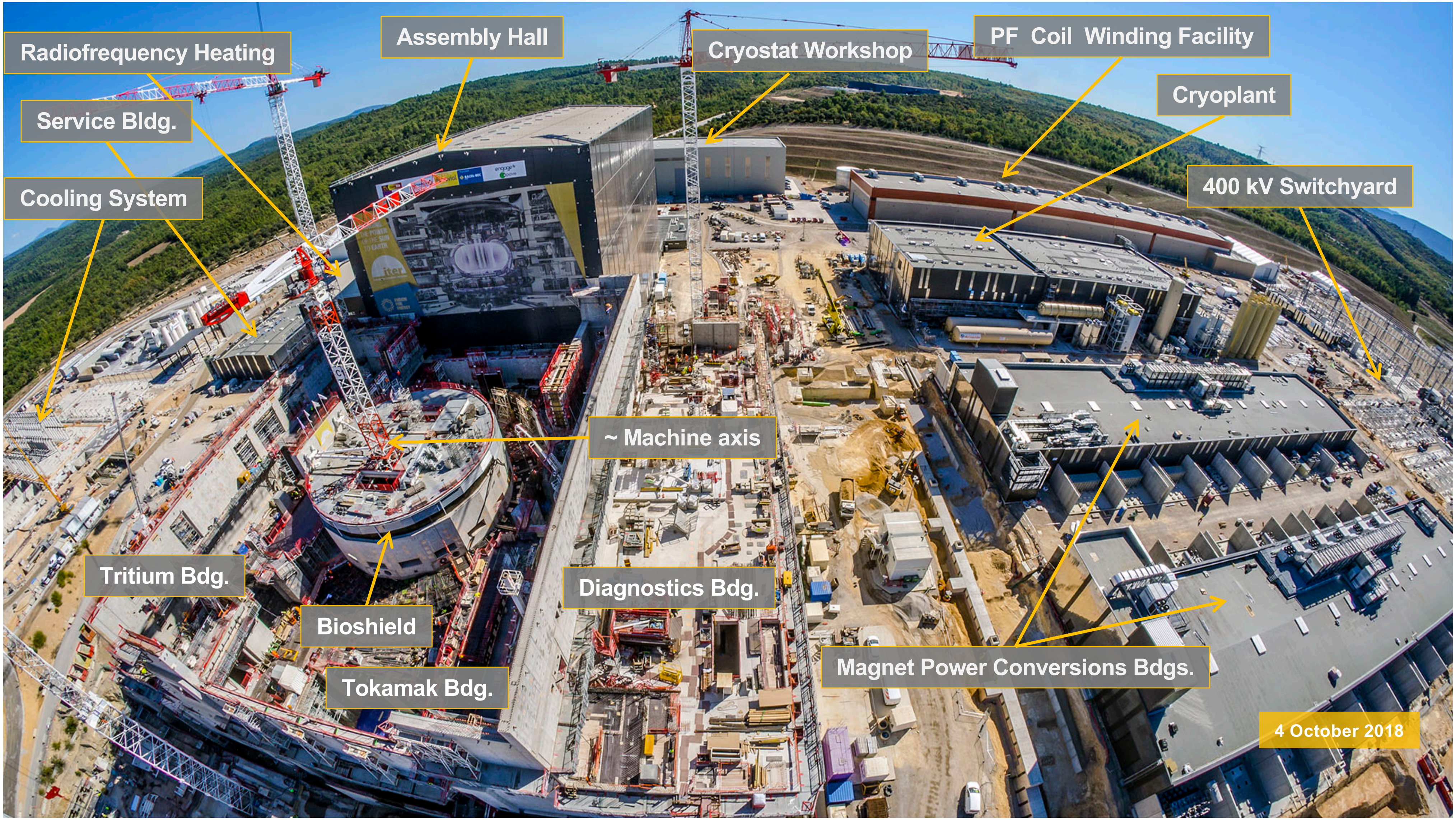
Site preparation was finished in 2009 over a 4-year period

The construction of the ITER buildings commenced in September 2011



Aerial view of the site in September 2013

The ITER work site on Oct 4, 2018



The ITER work site on February 2020

Progress on the work site Nov 2014 versus Nov 2020: 75% of the civil engineering work is completed

Six years of steady progress

Bigot, Fusion Power Associates, Dec 2020

November 2014

November 2020

More than 75% of the installation's civil works are now completed.

iter china eu india japan korea russia usa

Fusion Power Associates Annual Meeting, 16 December 2020

Page 4/25

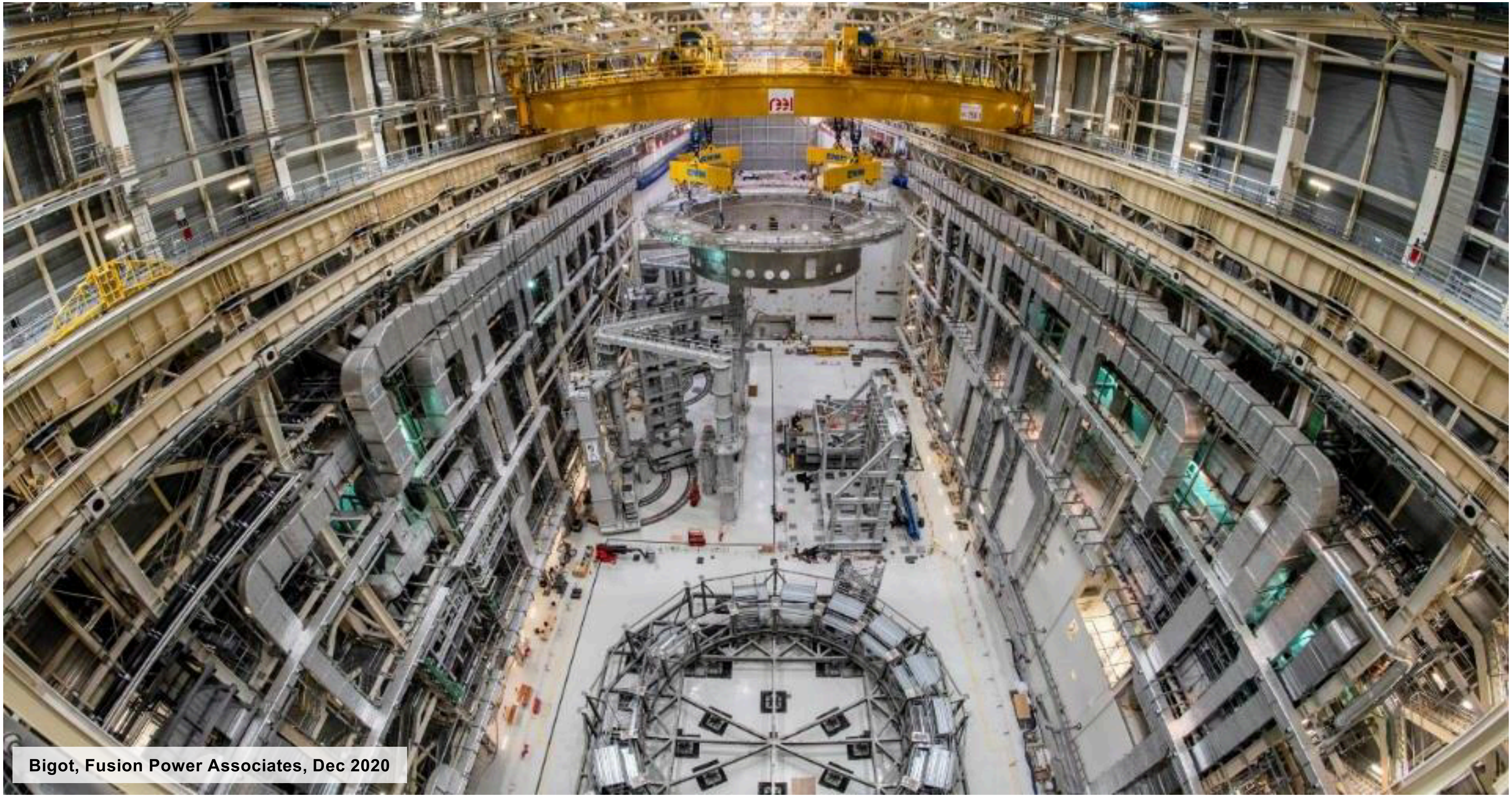
The ITER work site on November 2020

Bigot, Fusion Power Associates, Dec 2020

Site construction June 2020: ITER by drone

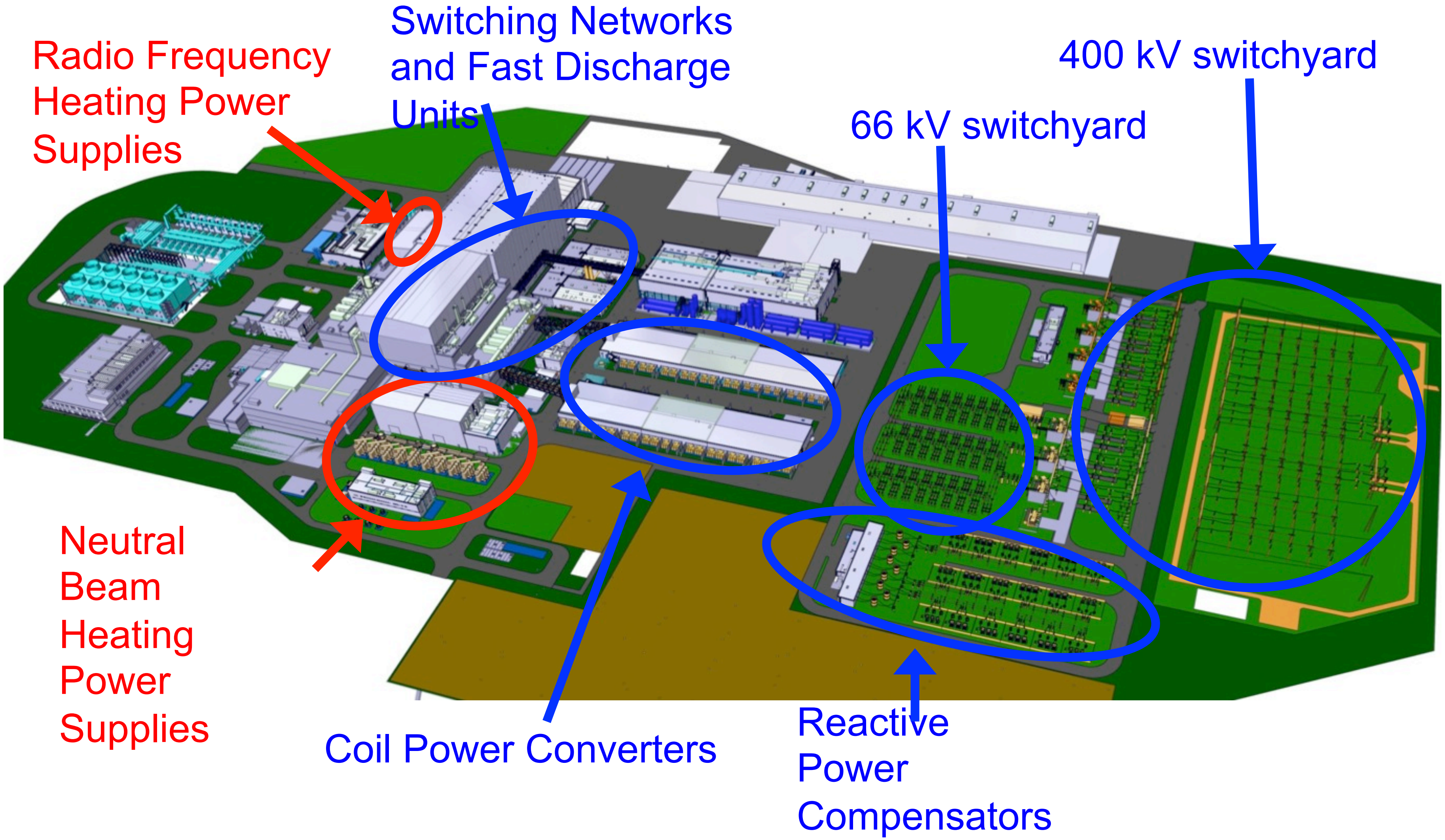
https://www.youtube.com/watch?v=_7-pvJ8lRBg

In May 2020, the base of the Cryostat (1,250 t) was successfully inserted into the tokamak assembly pit

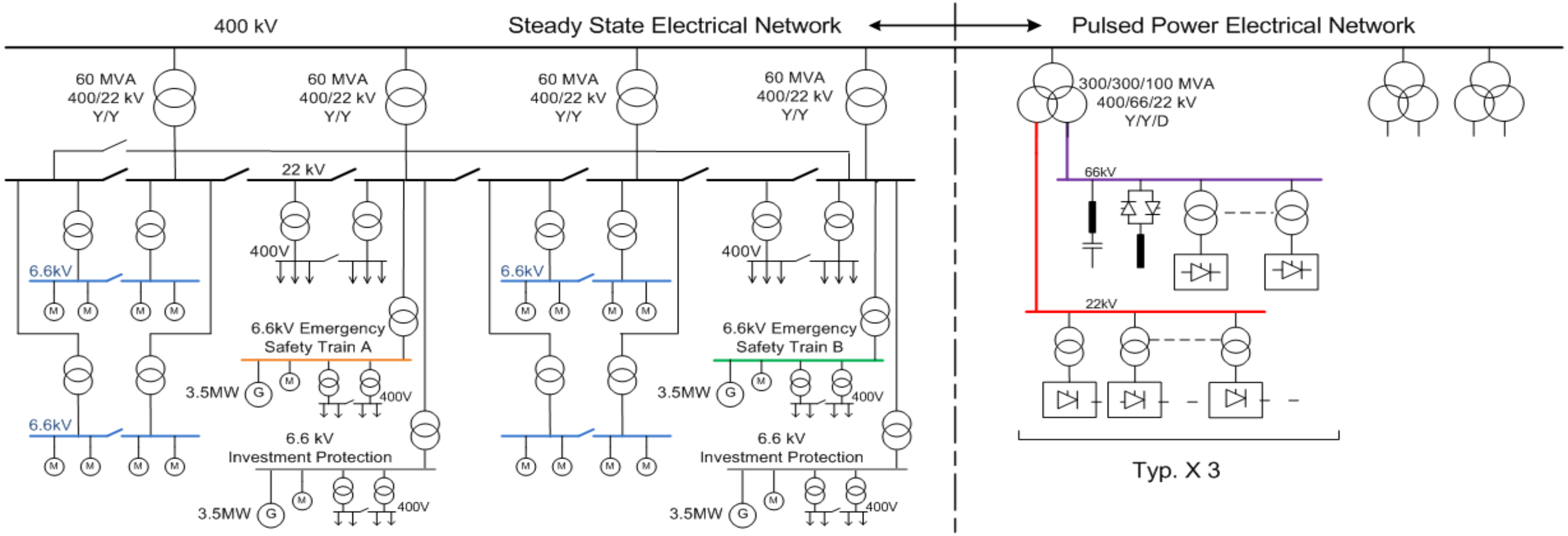


Bigot, Fusion Power Associates, Dec 2020

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

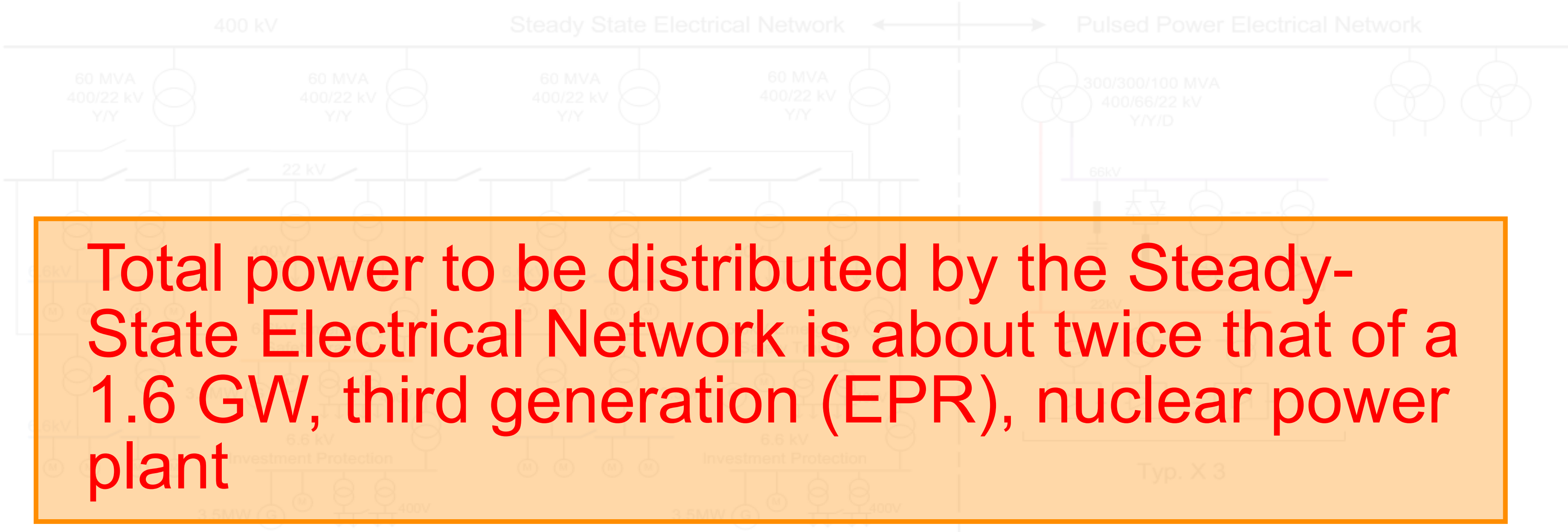
about 500 MW peak pulse

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:

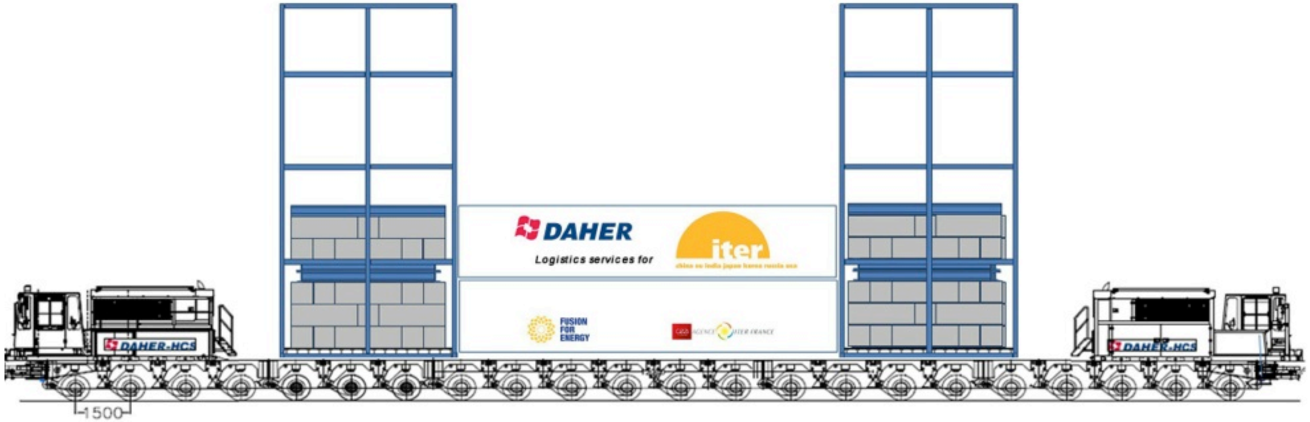
- Coil power converters
- Radio Freq. and Neutral Beam systems

Includes large Static Var Compensators

Large components arriving in France must be transported ~100 km from the coast to Cadarache

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

A 352-wheel test convoy carried 800 ton load through southern France in September 2013



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

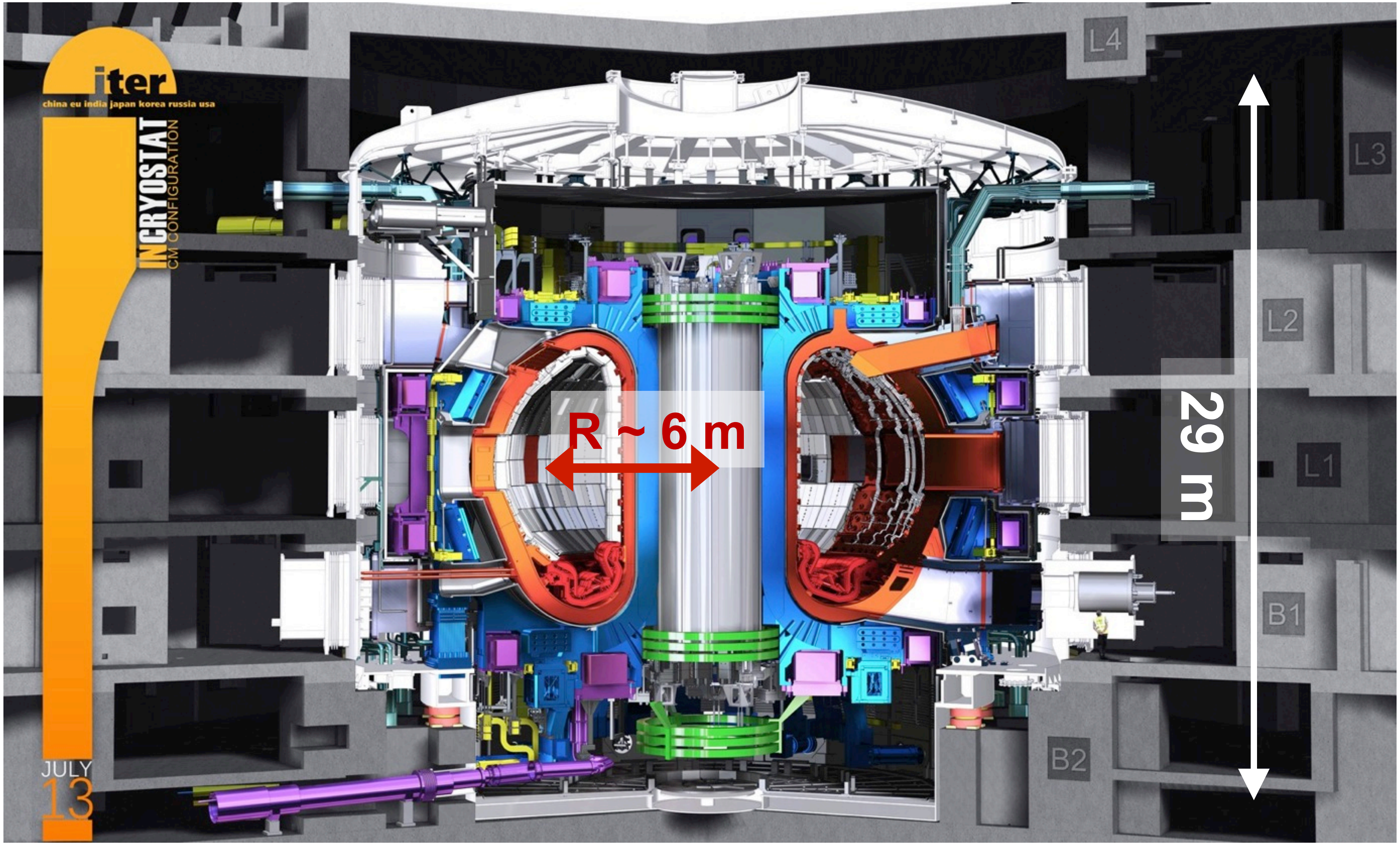
iter china eu india japan korea russia usa

Fusion Power Associates Annual Meeting, 16 December 2020

Page 13/25

Bigot, Fusion Power Associates, Dec 2020

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



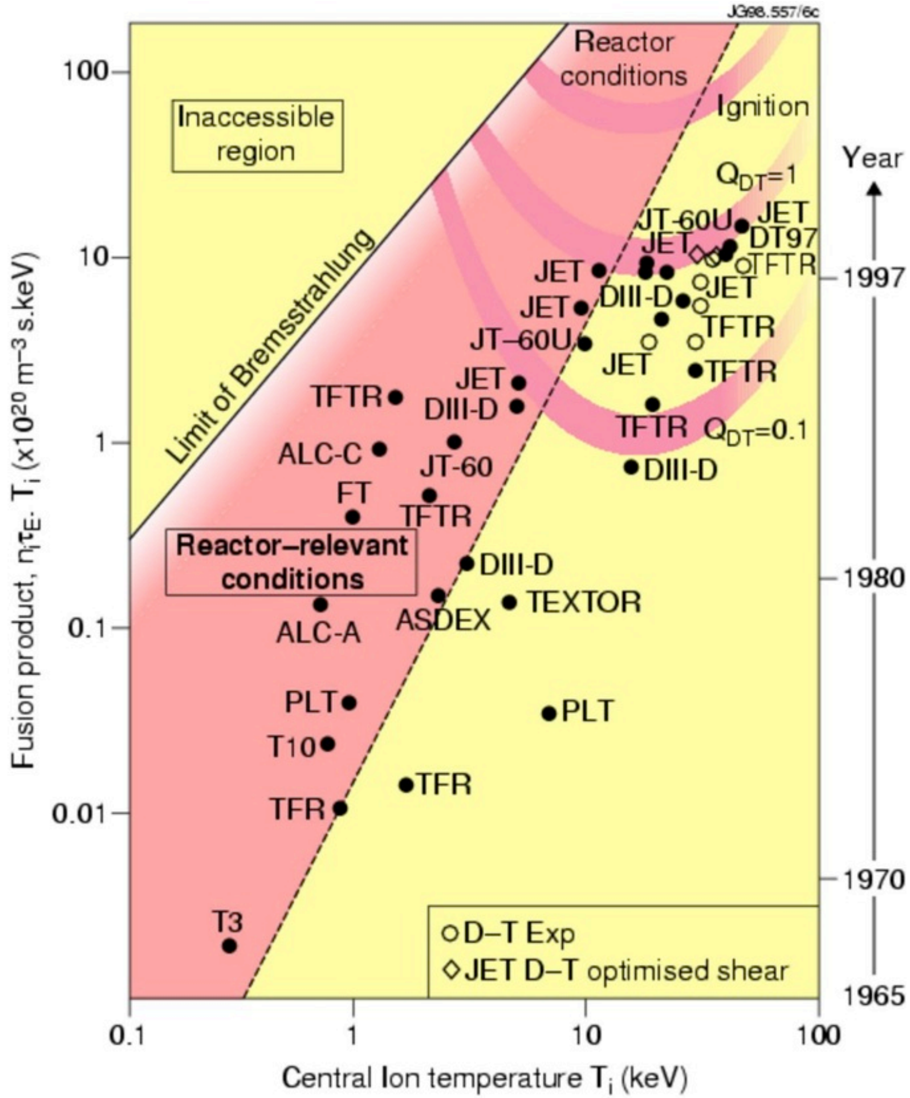
ITER is designed to integrate a burning plasma into the latest and future technology

- **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

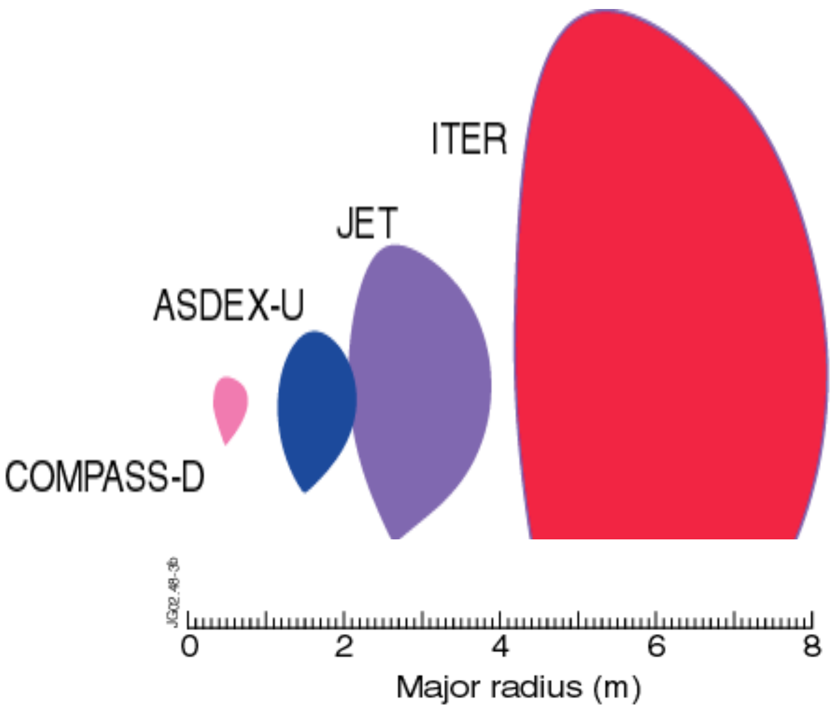
ITER is designed to yield $Q_{DT} \geq 10$ at a fusion power of up 500 MW for up to 500 s

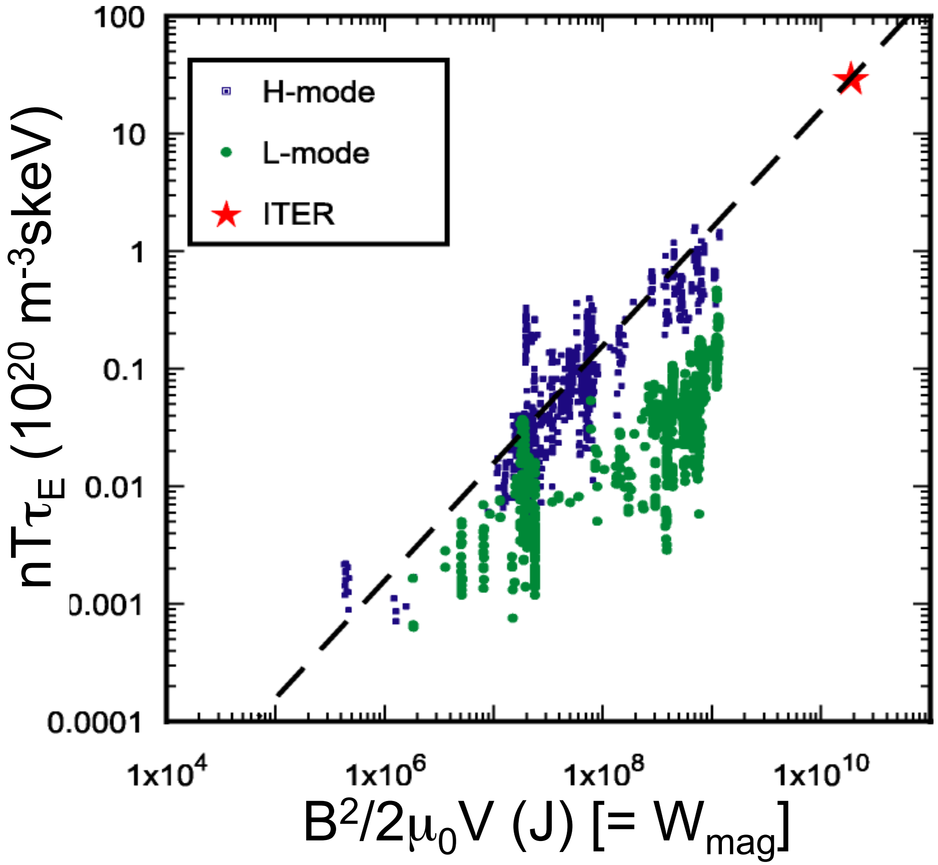
$$Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$$

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



Confinement scaling provides an approach to determine the size of ITER





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

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

- **Plasma is self-heated by fusion α-particles**
  - Non-linearity in total 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, fuelling, heating, stability, 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 is 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 is 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 is licensed as a Basic Nuclear Installation

- **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:**

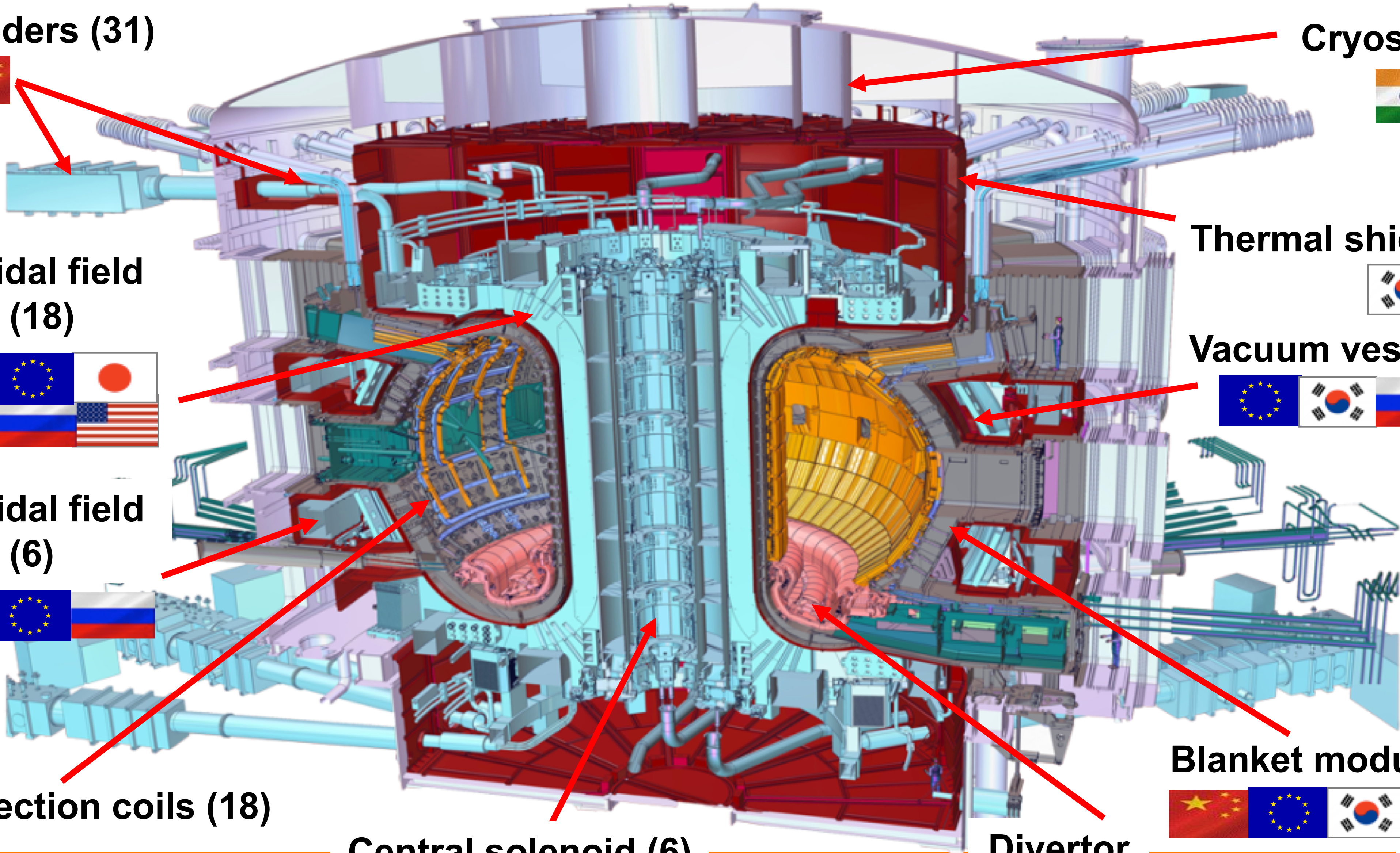
Arrêtés 2011/200/INB 23/5/11 et 2011/1245/INB 11/7/11 CONCLUSIONS Décision n° E11000025/13

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**

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



Feeders (31)

Cryostat

Thermal shield

Toroidal field coils (18)

Vacuum vessel

Poloidal field coils (6)

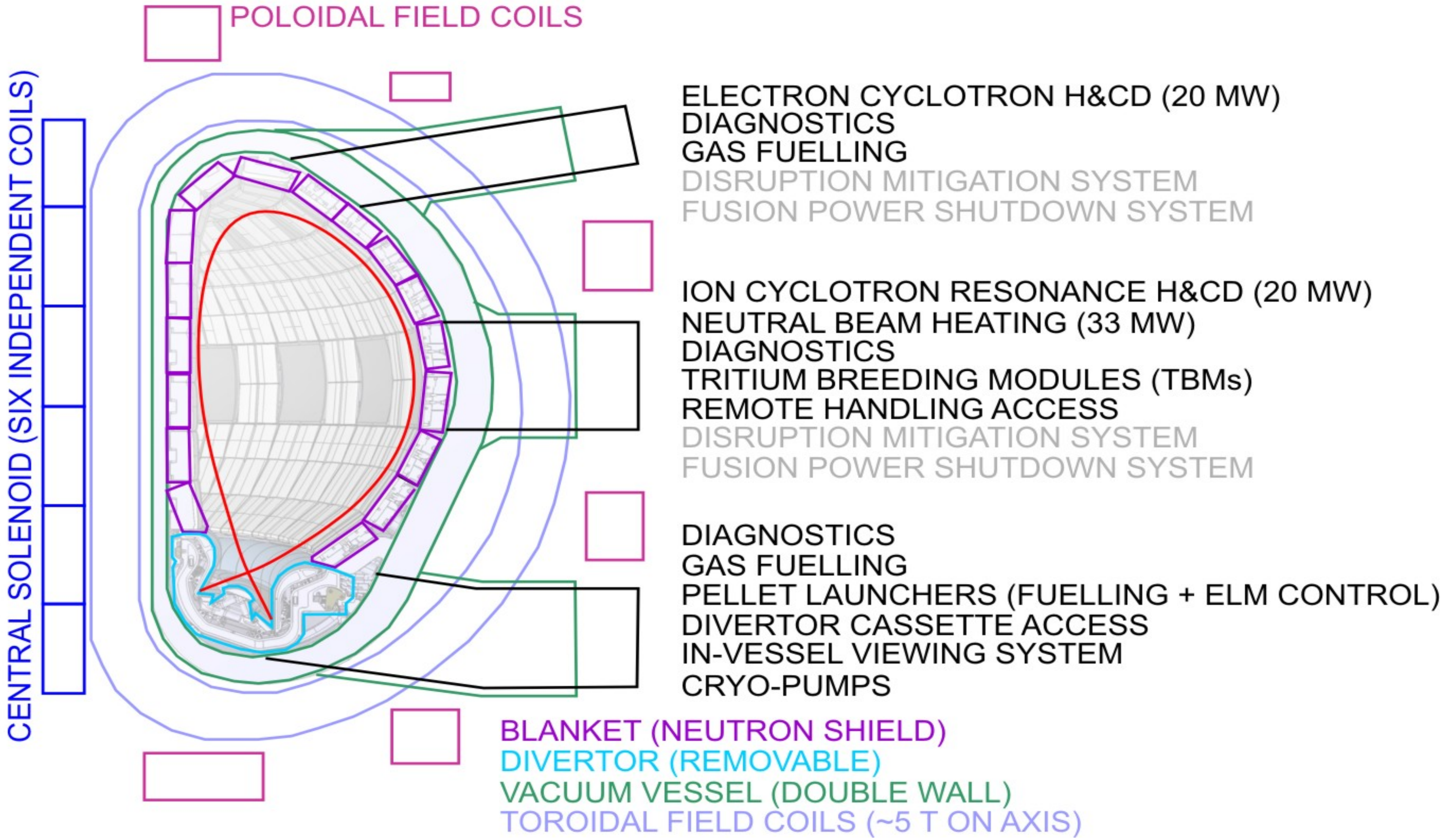
Blanket modules

Correction coils (18)

Central solenoid (6)

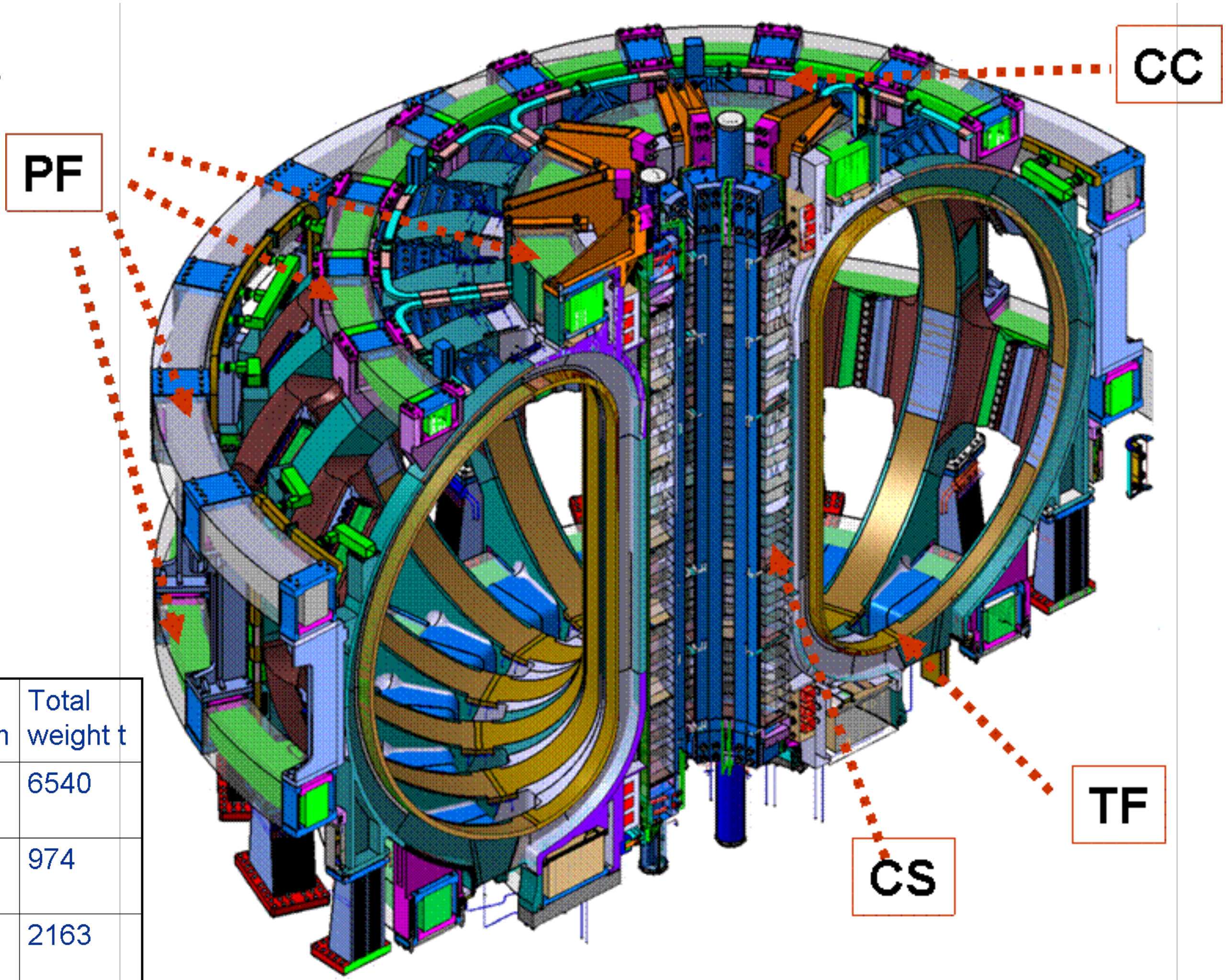
Divertor

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



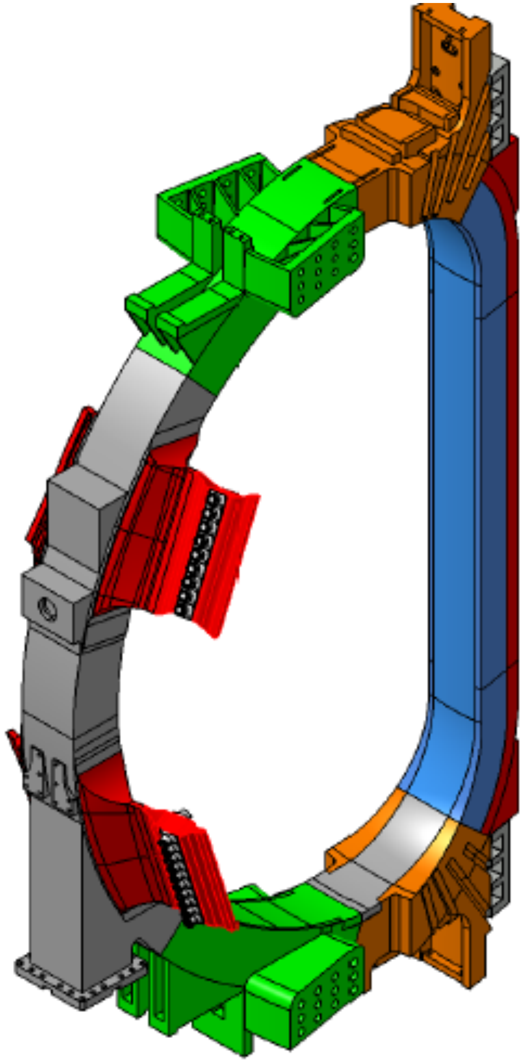
ITER consists of 48 superconducting magnetic coils

- **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

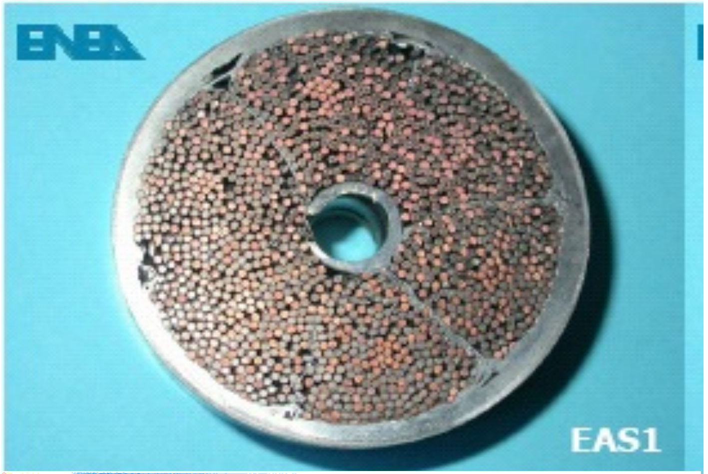
Each toroidal field coils has a total weight of approximately 360 tons

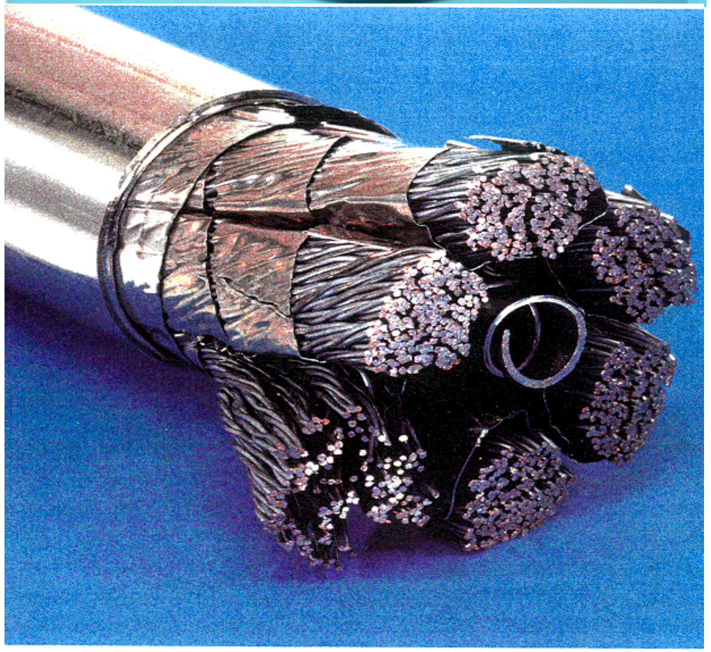


Boeing 747-300: (maximum takeoff weight ~377 t)

- **16 x 9 m, ~360 t**
- **Fabrication in the EU (Karlsruhe) and Japan (Toshiba): 18 coils**

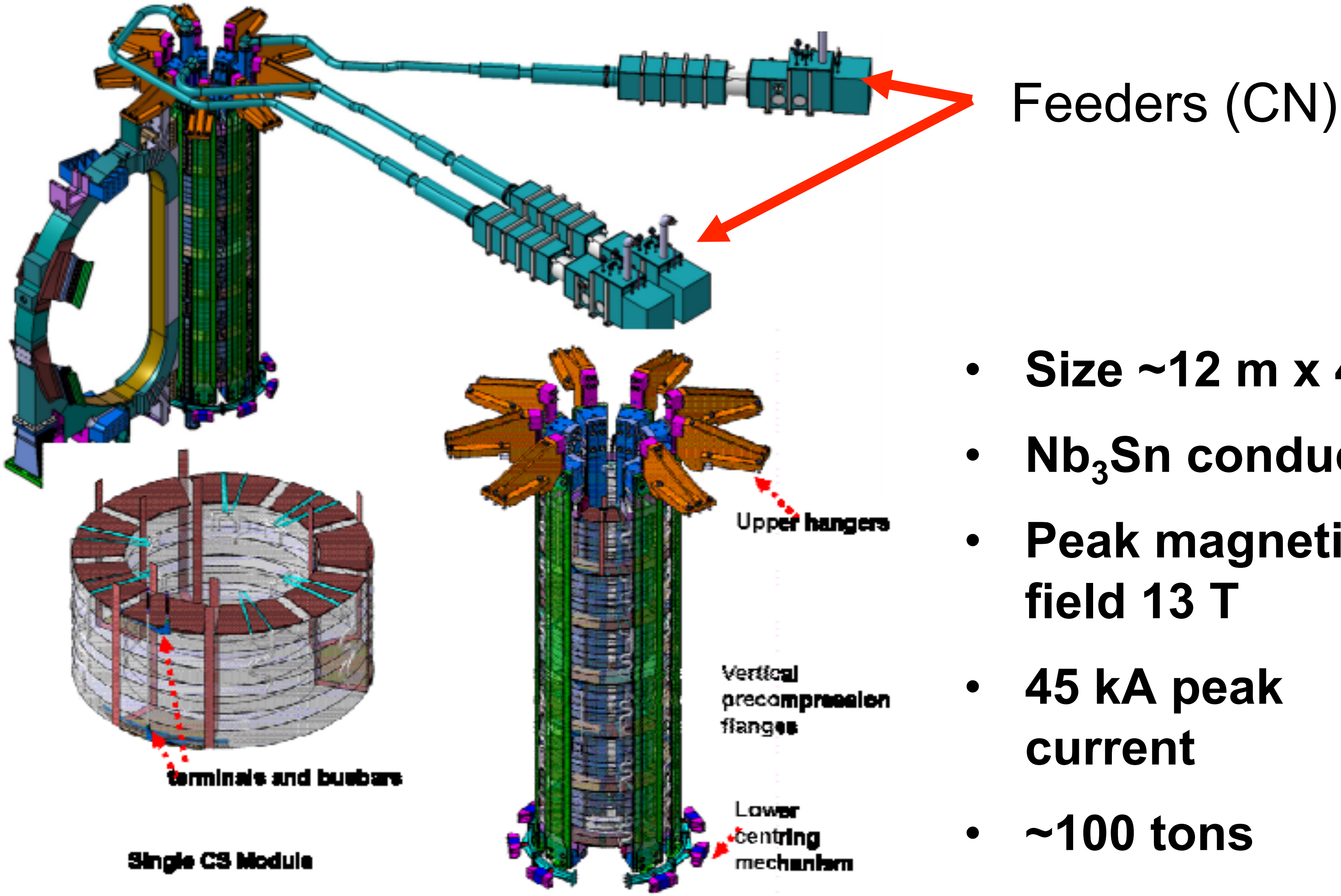
An unprecedented amount of superconductors is needed for ITER





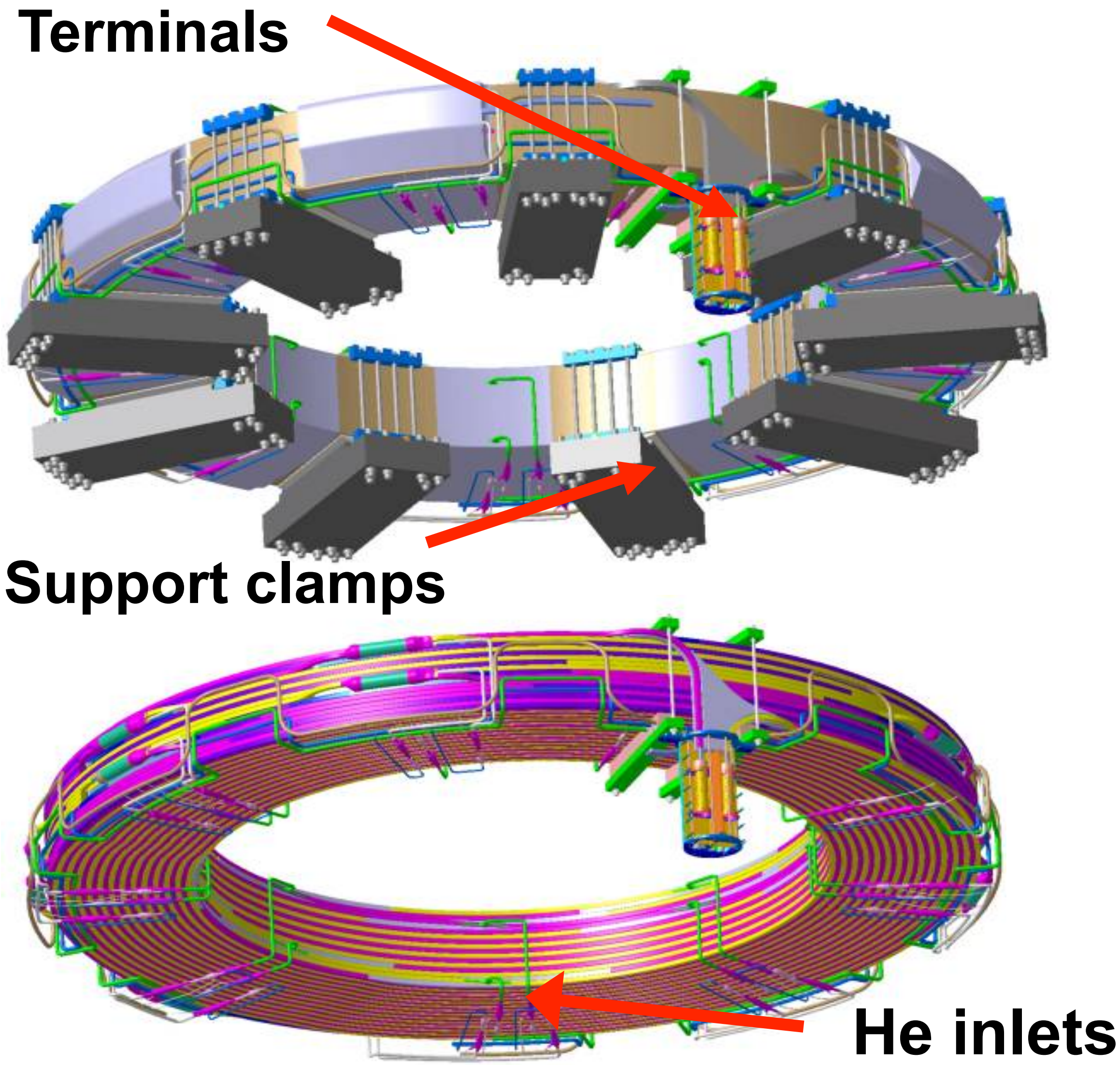
- ~90 km / 450 tons of Nb_3Sn
- ~ 150,000 km of strand
- Operation at ~5 K
- Peak magnetic field 11.8 T
- 68 kA peak current in coils
- Manufacture in EU, Japan, Russian Federation, China, Korea and US

The central solenoid coil stack consists of 6 independently powered modules

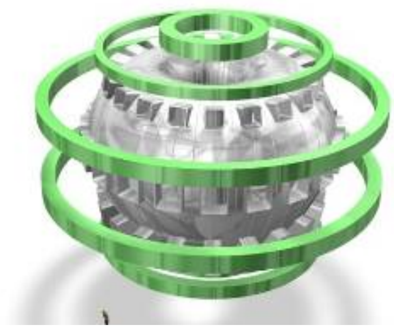


- Size ~12 m x 4 m
- Nb_3Sn conductor
- Peak magnetic field 13 T
- 45 kA peak current
- ~100 tons

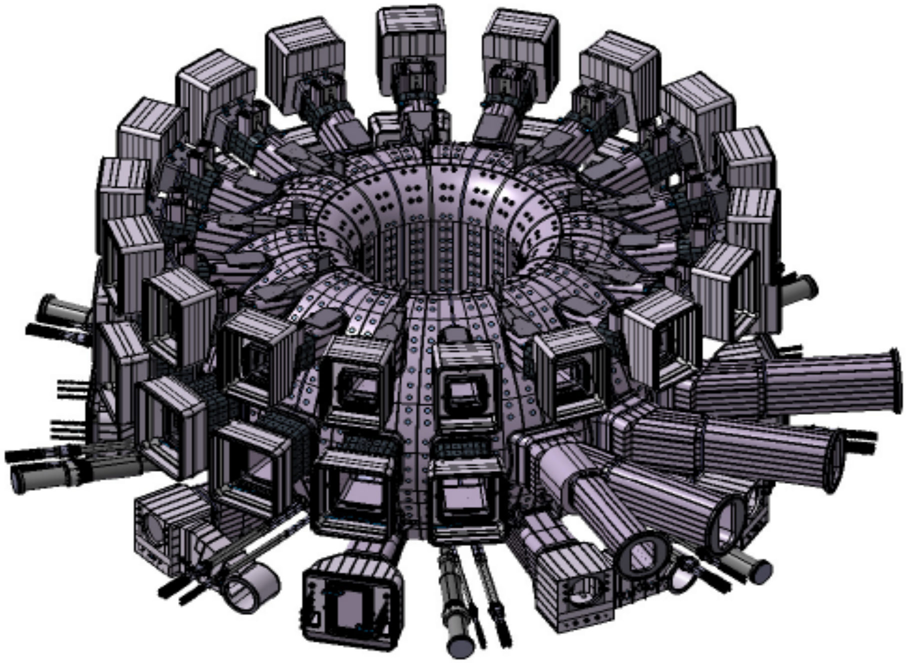
There are 6 poloidal field coils, made of NbTi

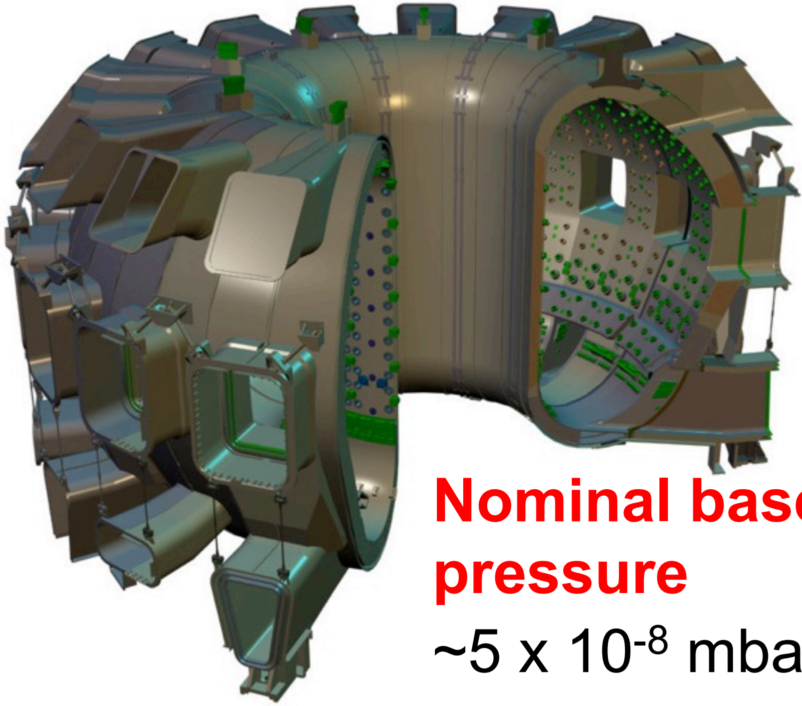


- **Up to 25 m in diameter**
- **6.8 T peak field**
- **55 kA peak current**
- **Manufactured on-site**



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



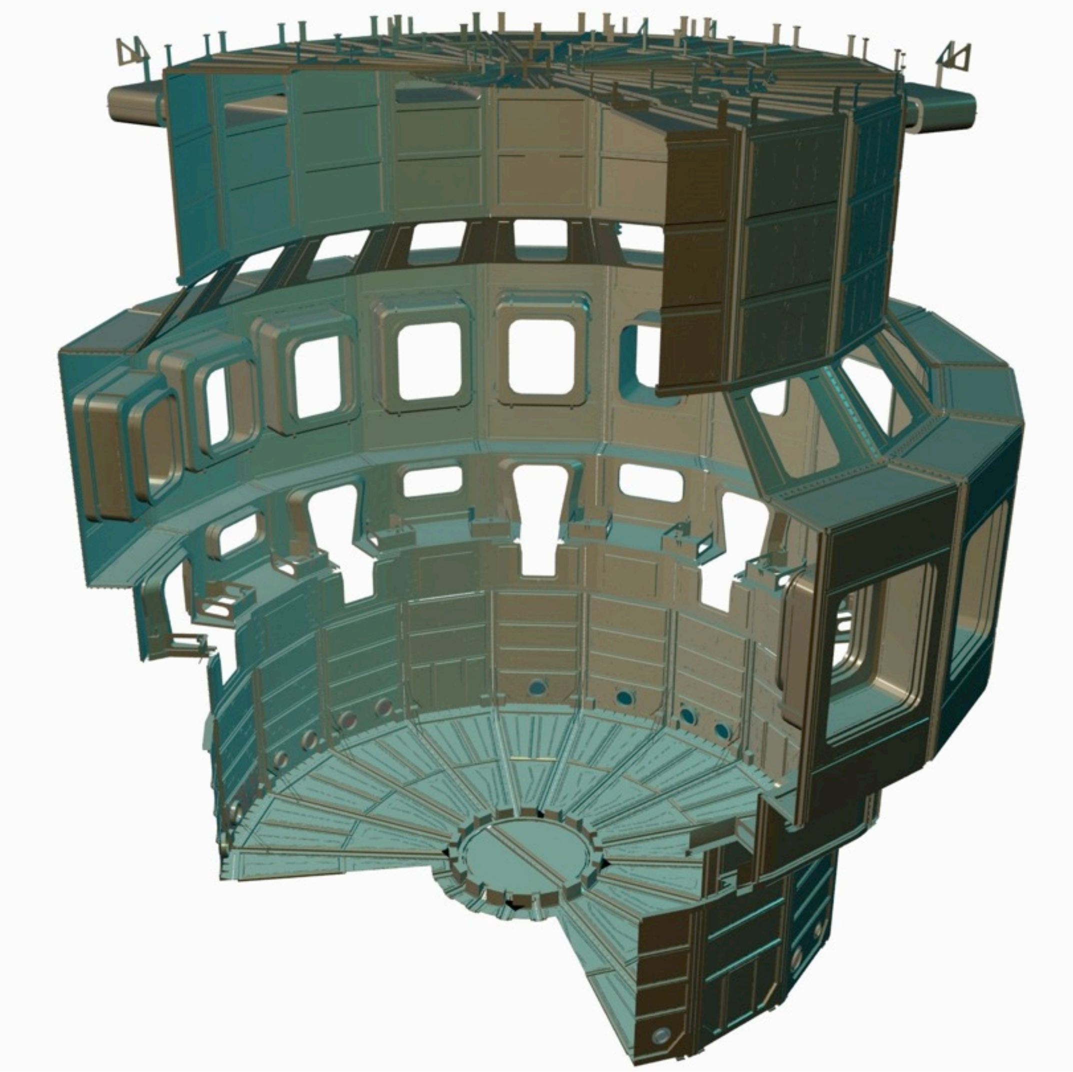


Nominal base pressure

~5 x 10^{-8} mbar

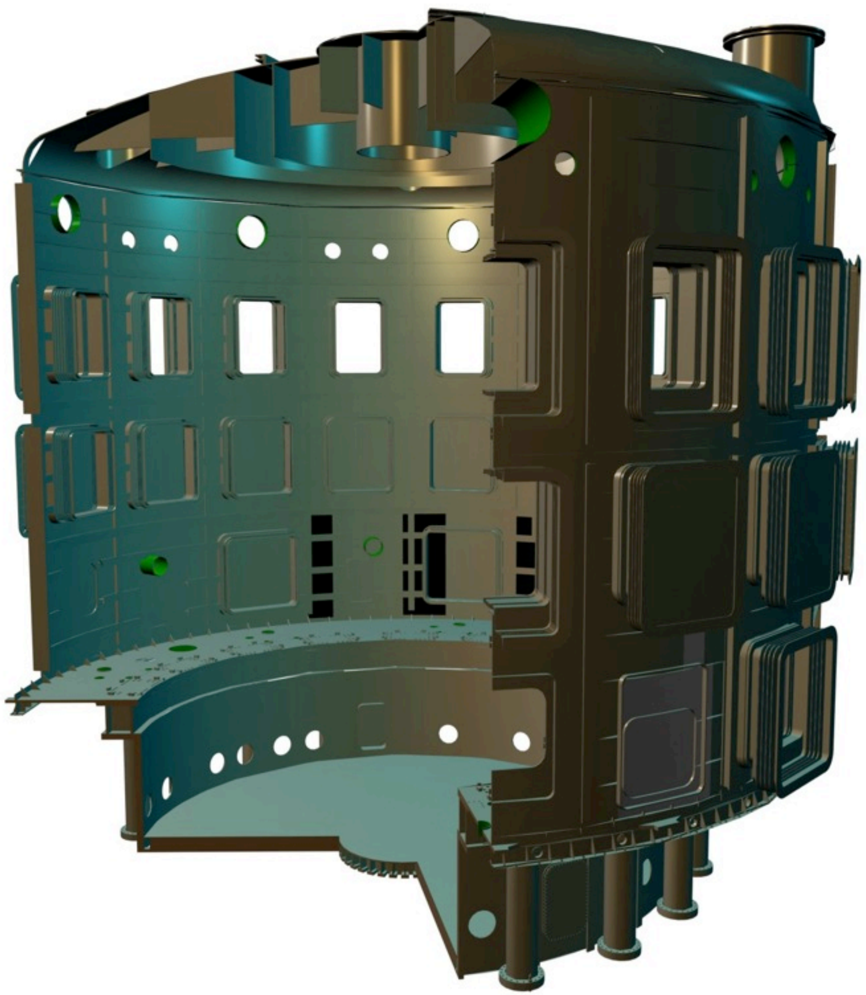
- **19.4 m outer diameter, 11.3 m height**
- **SS 316 L(N)-IG**
- **Primary tritium containment barrier, bakeable to 200° C**

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



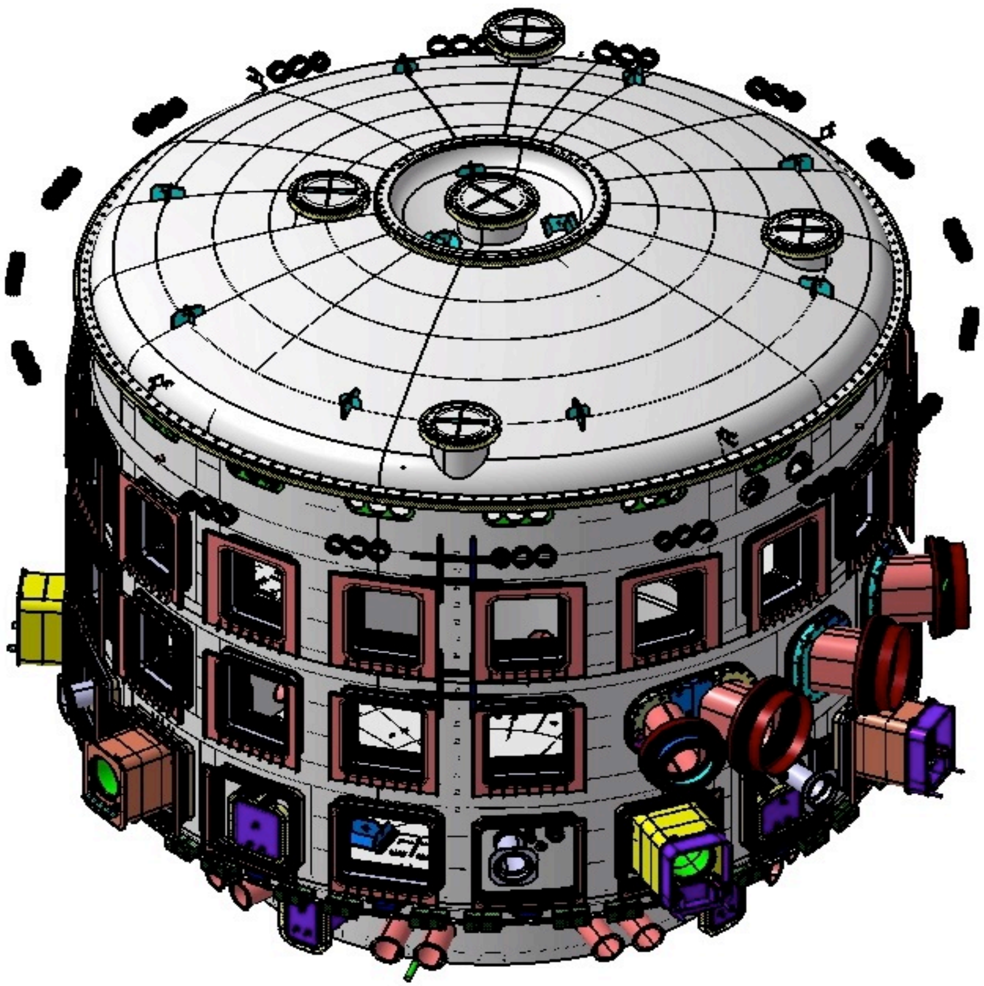
- Operates at 80 K (gaseous He in cooling pines)
- Stainless steel panels are silver coated to reduce emissivity
- Total mass ~ 1000 t
- Smaller shield isolates TF coils from vacuum vessel

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

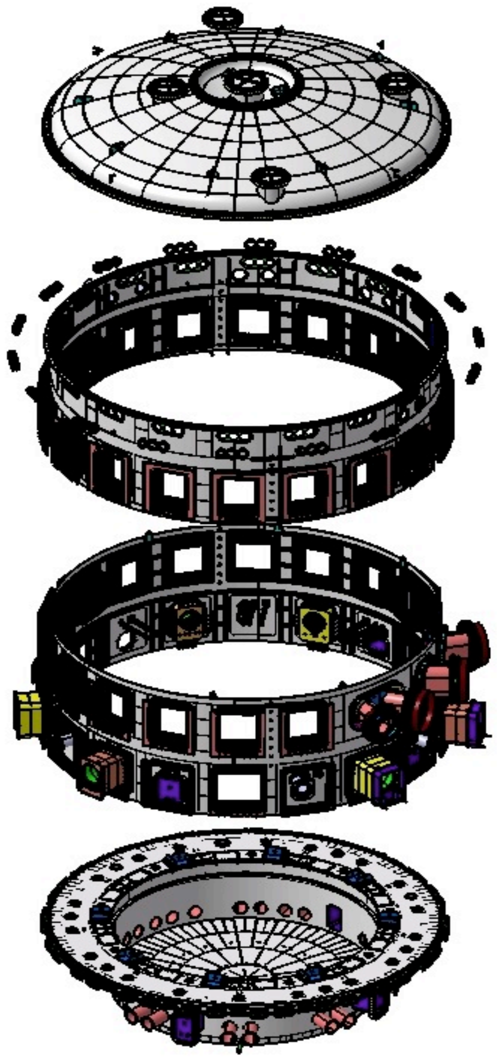


Top lid

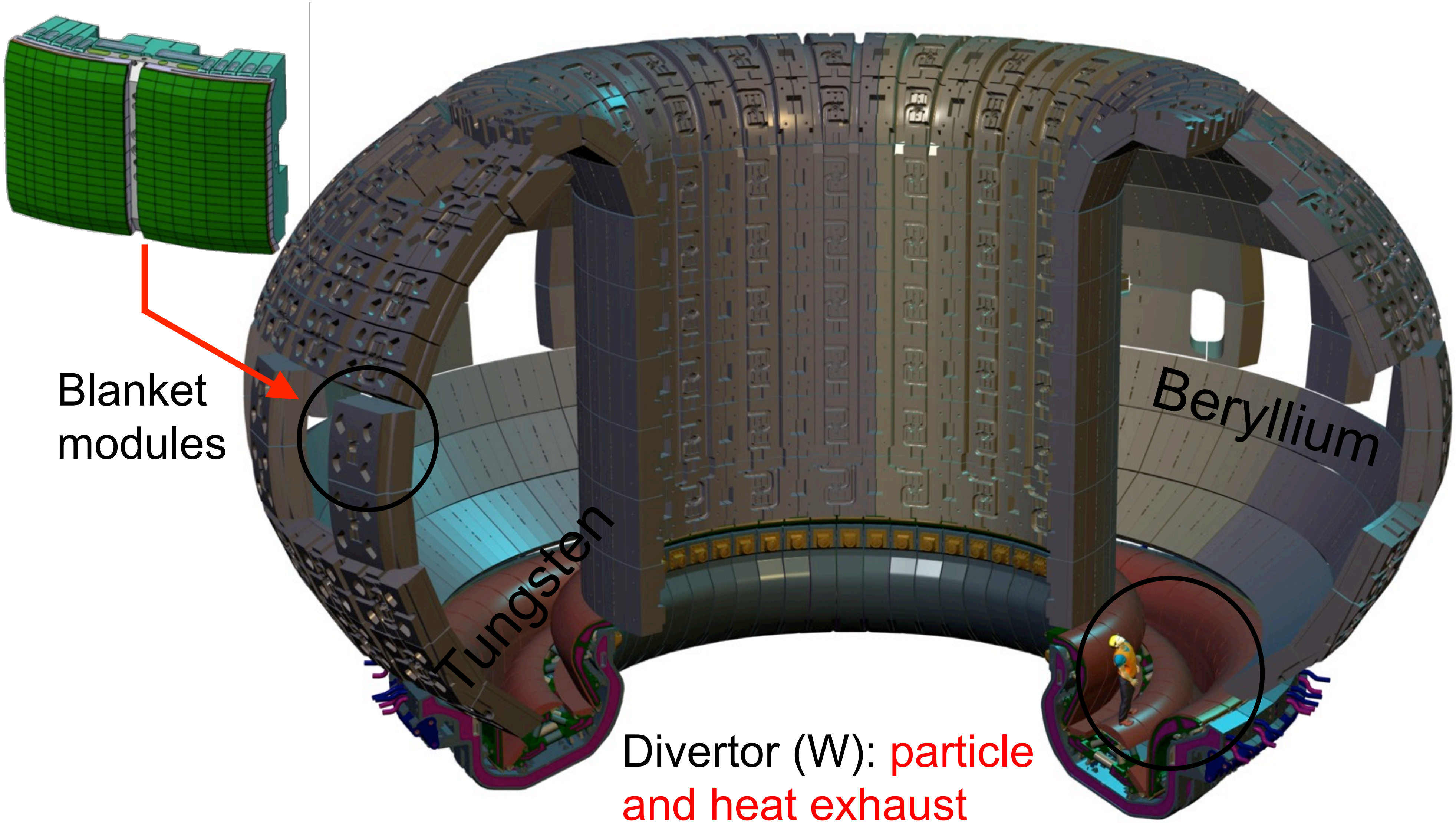
Upper cylinder

Lower cylinder

Base section



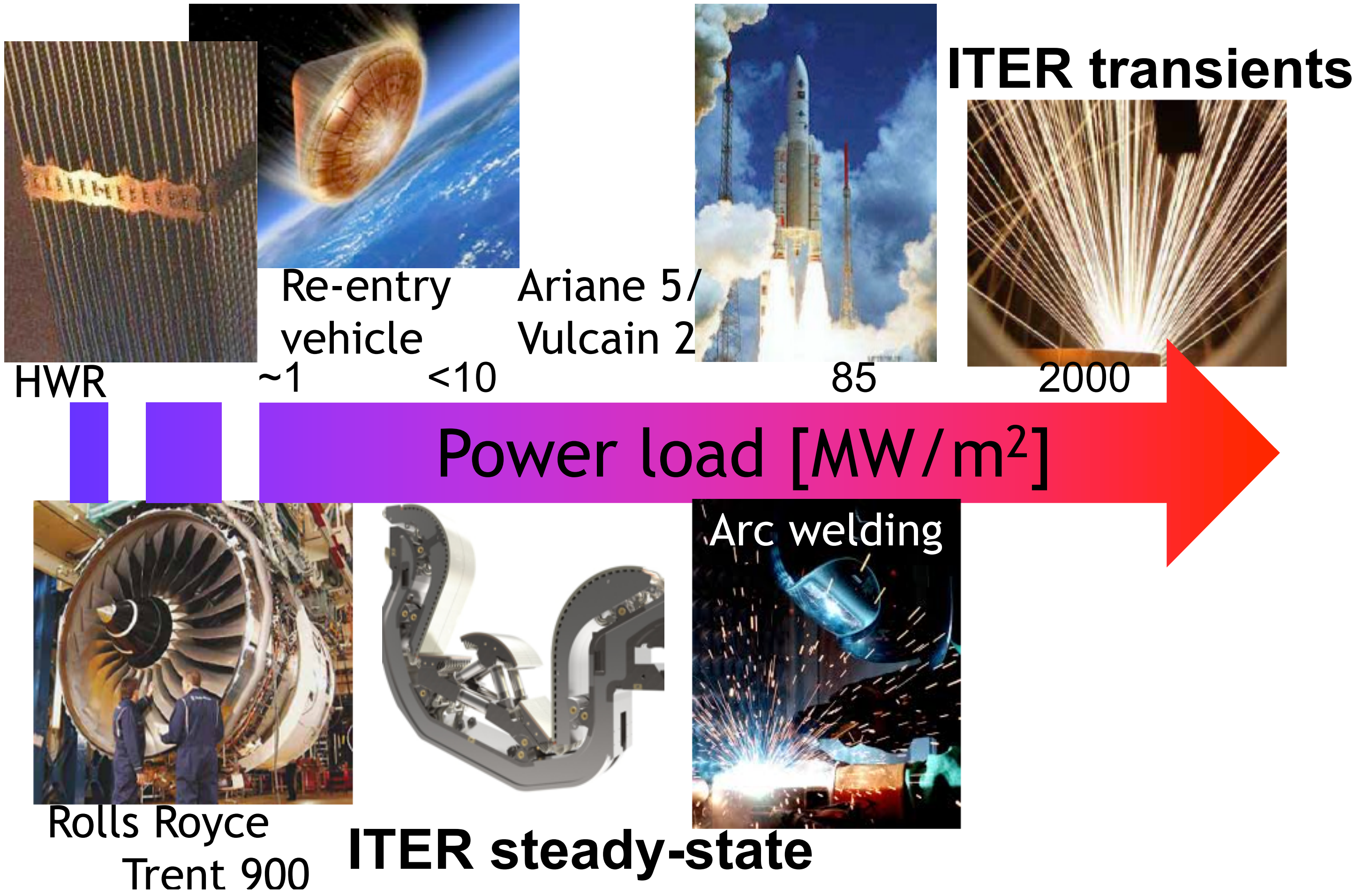
The first wall, or blanket, provides the interface of the machine to the (burning!) plasma



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

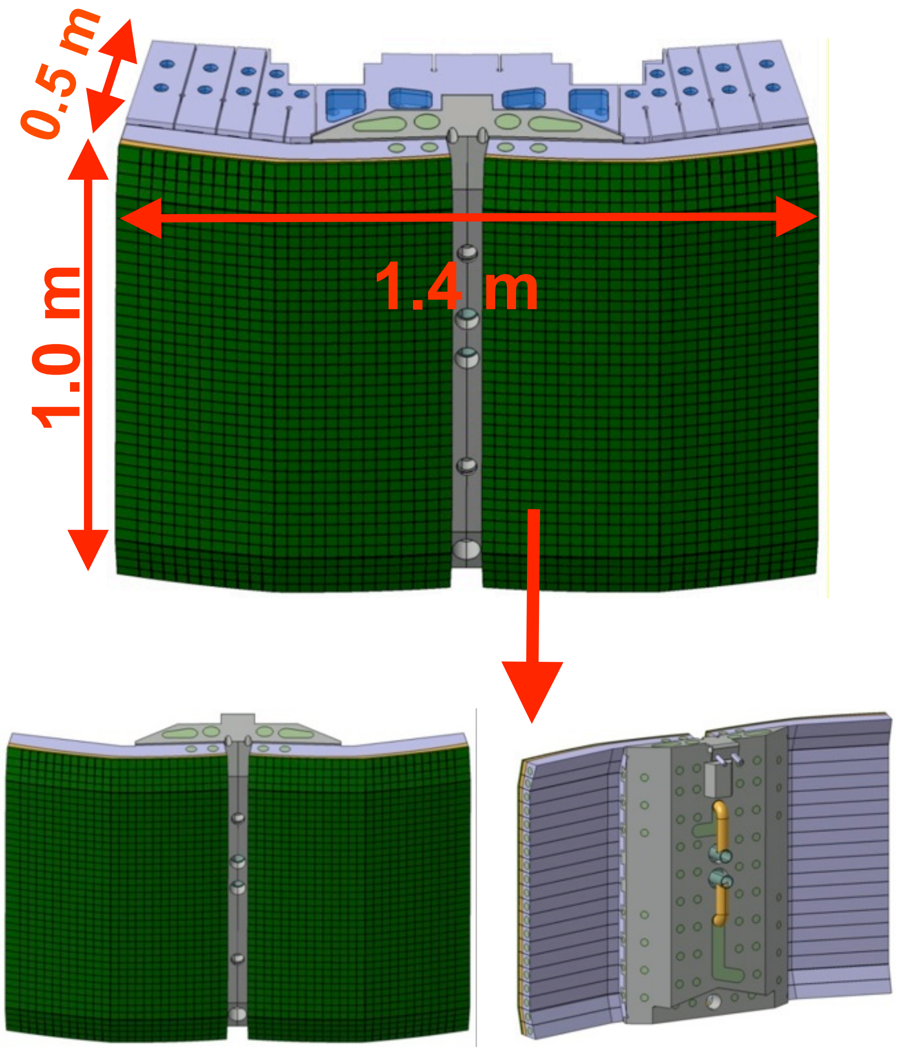
The challenge is not small!

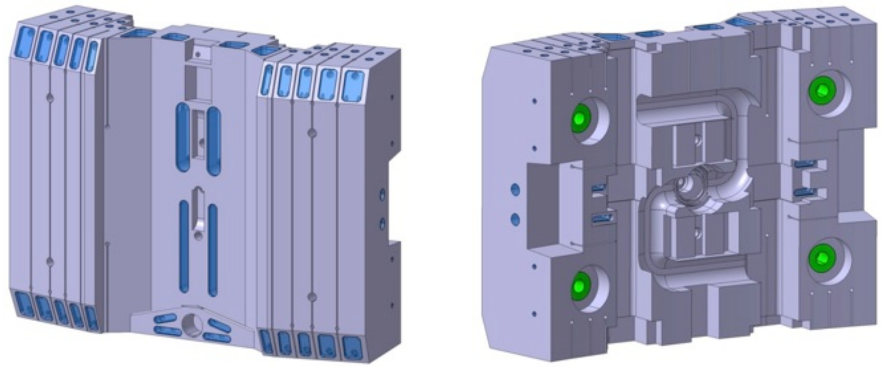
The consequences of failing to protect in-vessel components are big—components are actively cooled (water) and replacement time is months



Luce, APS-DPP Oct 2018

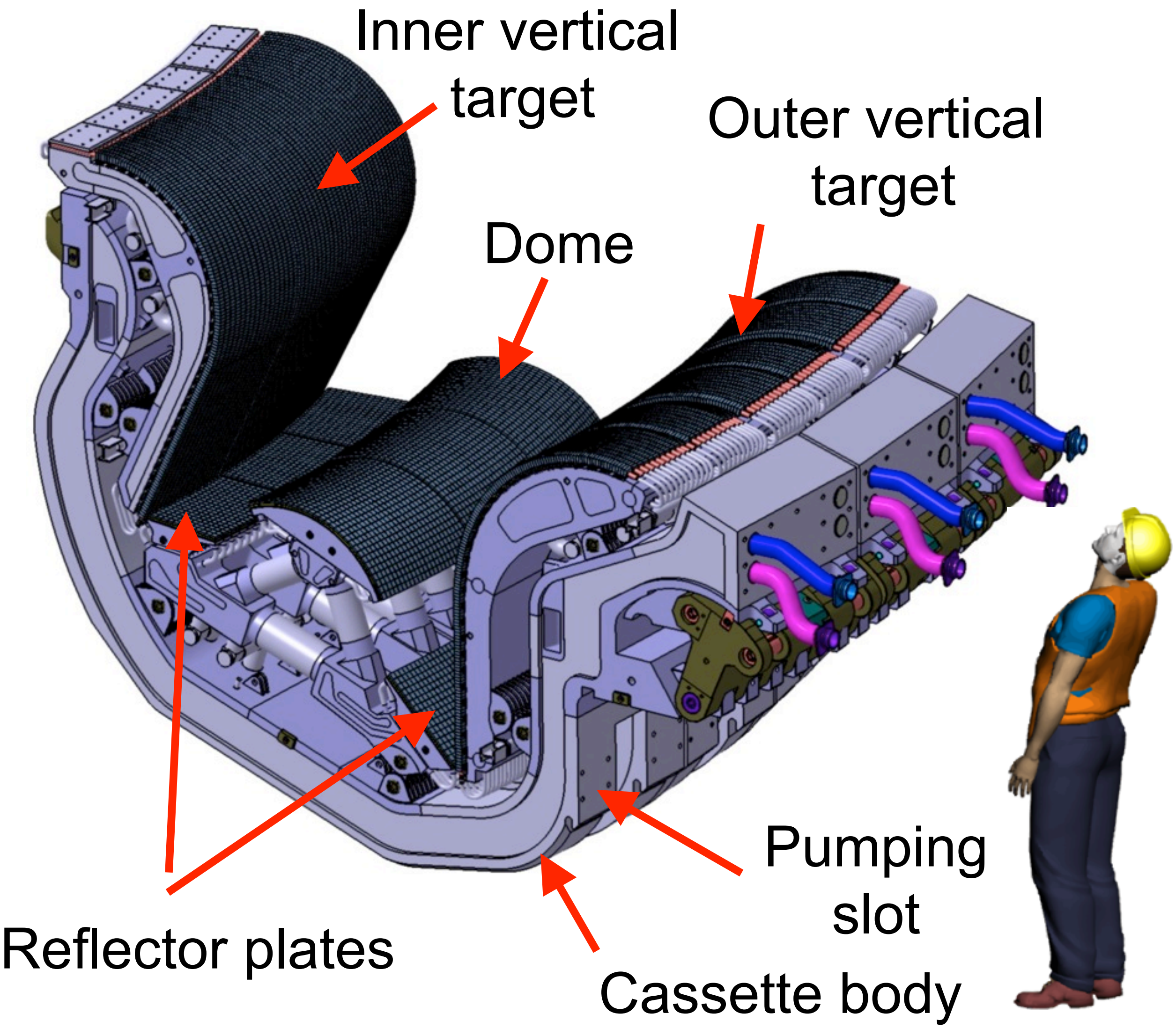
The first-wall blanket modules provide both neutron and plasma shielding





- **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)**

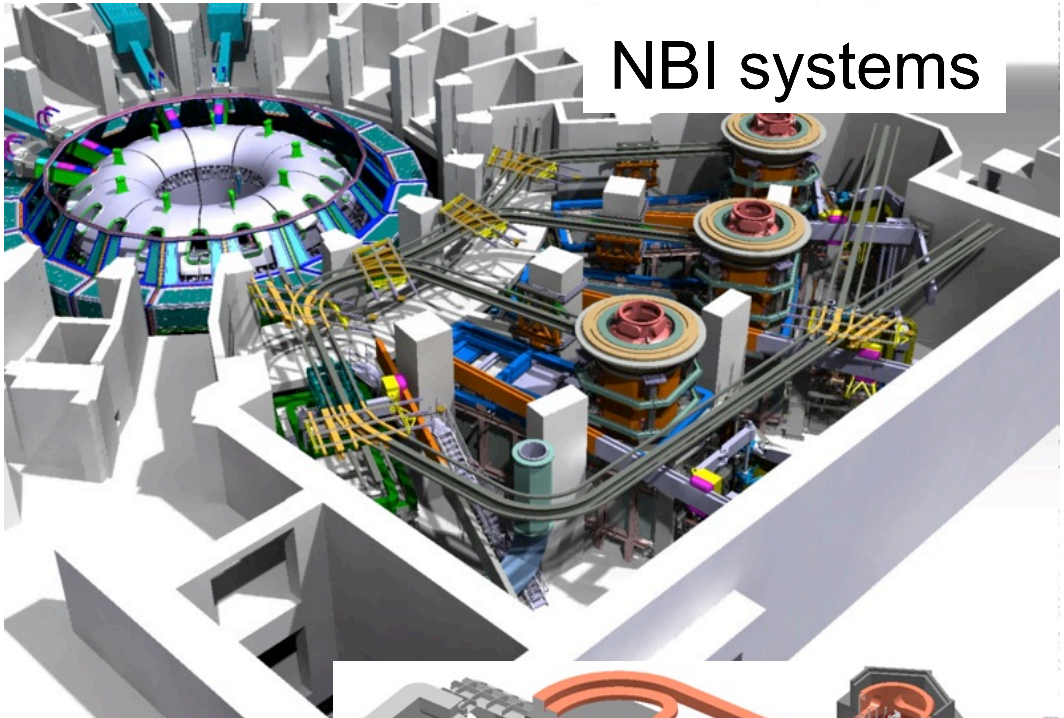
The divertor consists of 54 cassettes (~ 8.7 t each) bakeable to 350° C

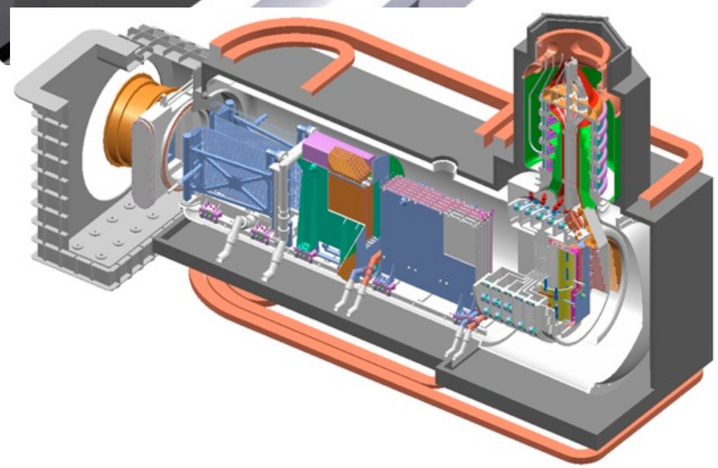


- **4320 actively cooled heat flux components**
- **Divertor PFCs are made of tungsten**
- **Removable cassettes**

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

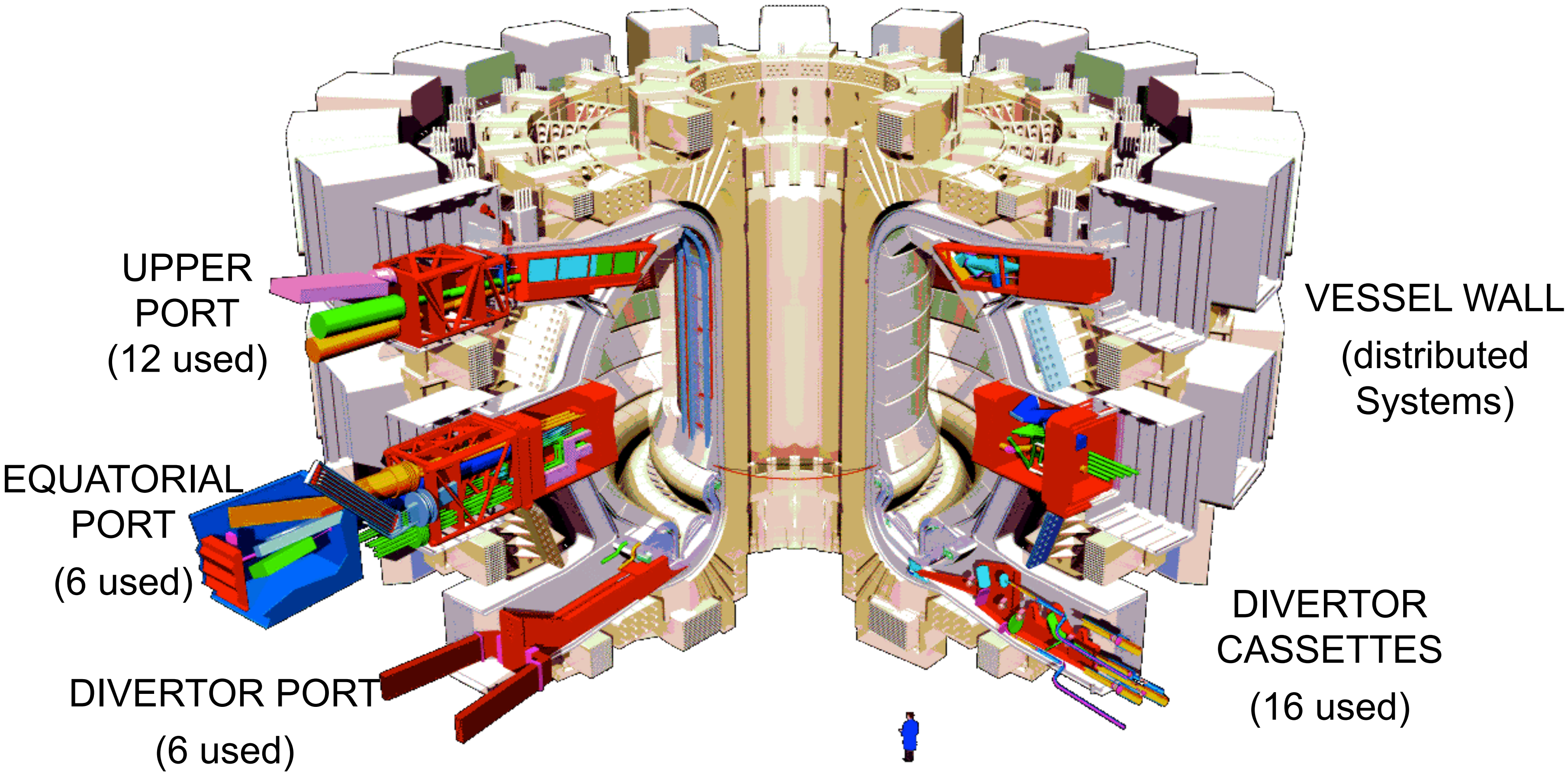
System	Power
NBI –ve ion, 1 MeV	33 MW
ECH & CD 170 GHz	20 MW
ICRH & CD 40 – 55 MHz	20 MW





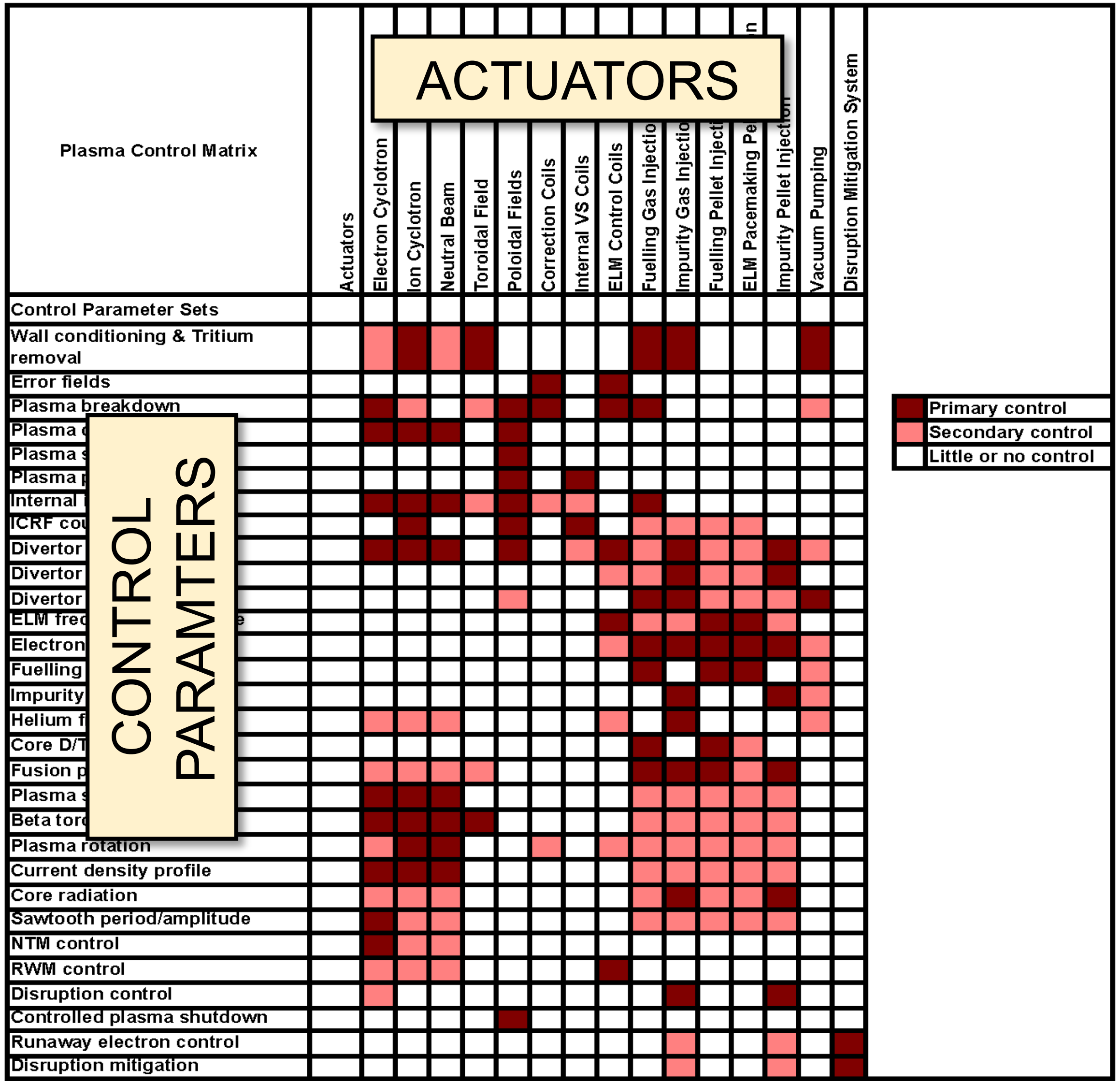
- **P_{aux} for Q_{DT} = 10 about 40-50 MW**
- **Upscale of known technology**
- **Modular for upgrades**

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



- **Daily (raw) data output is expected to reach petabytes**

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



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

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, licensing of project**
- **Construction of buildings and components (off-site) commenced in 2009 ⇒ by November 2020, 75% of the civil engineering work was completed ⇒ construction of actual tokamak started**
- **The first plasma (non-nuclear, hydrogen or helium) is anticipated for 2025, the first D-T Q=10 plasma in 2035**

ITER is moving forward