ITER: the next step

R. A. Pitts

ITER Organization

Science and Operations Department

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

Outline

First, a CAVEAT: the ITER project is a huge undertaking. This talk can only give a flavour of the overall development

Introduction: what is ITER?

- Partnership and procurement sharing

ITER scale size and baseline operational regime

Some key ITER components

The ITER site and construction progress

Outline

Introducing the "ITER standard man": he'll be making a few guest appearances throughout this talk (he's about 1.70 m)

First, what is ITER?

A major international collaboration in fusion energy research involving Europe (+ Switzerland), China, India, Japan, the Russian Federation, South Korea and the USA

EU, CN, IN, JA, RF, KO, US

Overall programme objective:

- to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

Principal goal:

- to design, construct and operate a tokamak experiment at a scale which satisfies this objective

ITER is designed to confine a DT plasma in which α-particle heating dominates all other forms of plasma heating → a burning plasma experiment

ITER and scale

Size: moving beyond the "human scale"
- Almost all components are "uncomfortably large"
- Can be a challenge for industry

Cost: will never know real cost (due to in kind procurement) but will probably be around 3-4x total intrinsic cost
- Difficult for politicians

Time: construction around 15 years, ~20 years of operation
- Difficult for politicians (and physicists)
- Maintenance periods will be difficult and lengthy (nuclear device)

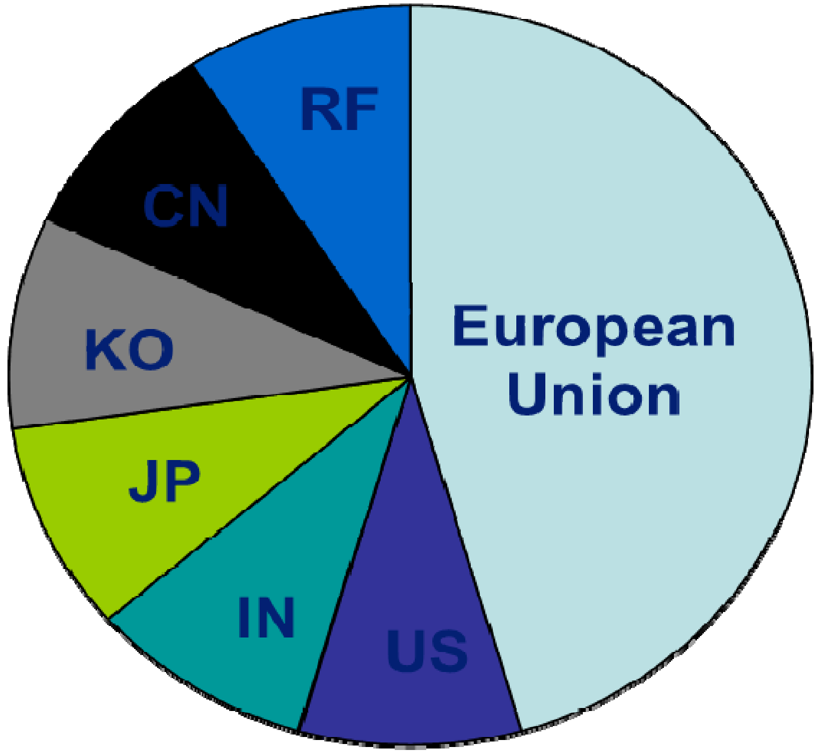
Complexity: highly integrated components, built in different places
- Large effort to manage "interfaces" and establish and enforce quality assurance (QA) procedures → has contributed to delays in the project

ITER construction sharing

A unique feature of ITER is that almost all (~90%) of the machine will be constructed through in-kind procurement from the Parties

Total intrinsic value = **4585 kIUA** (7826 M€ at kIUA 2015 rate)

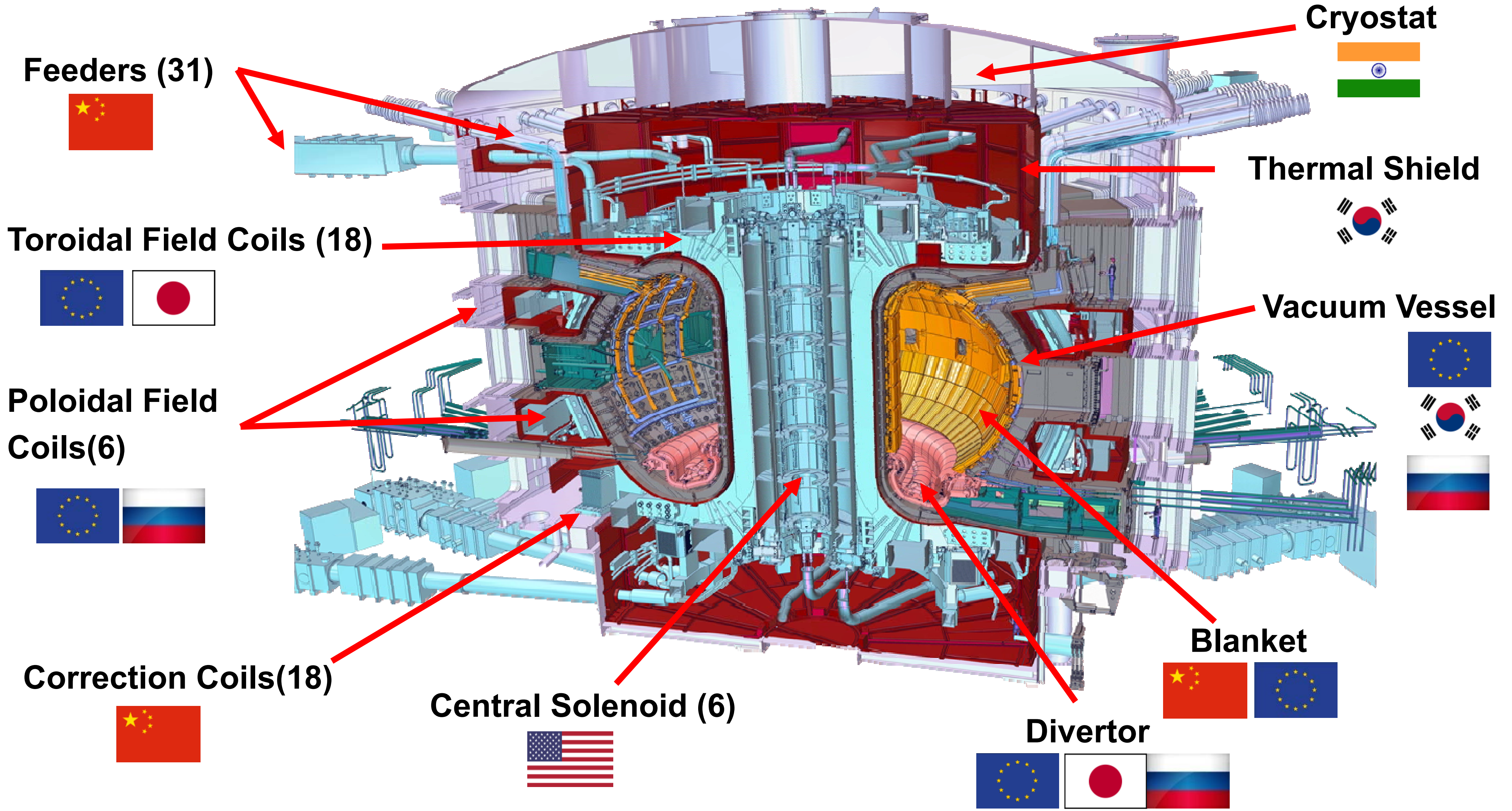
– Commercial value may be higher ….



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

Who manufactures what?

All intellectual property is shared by the seven members

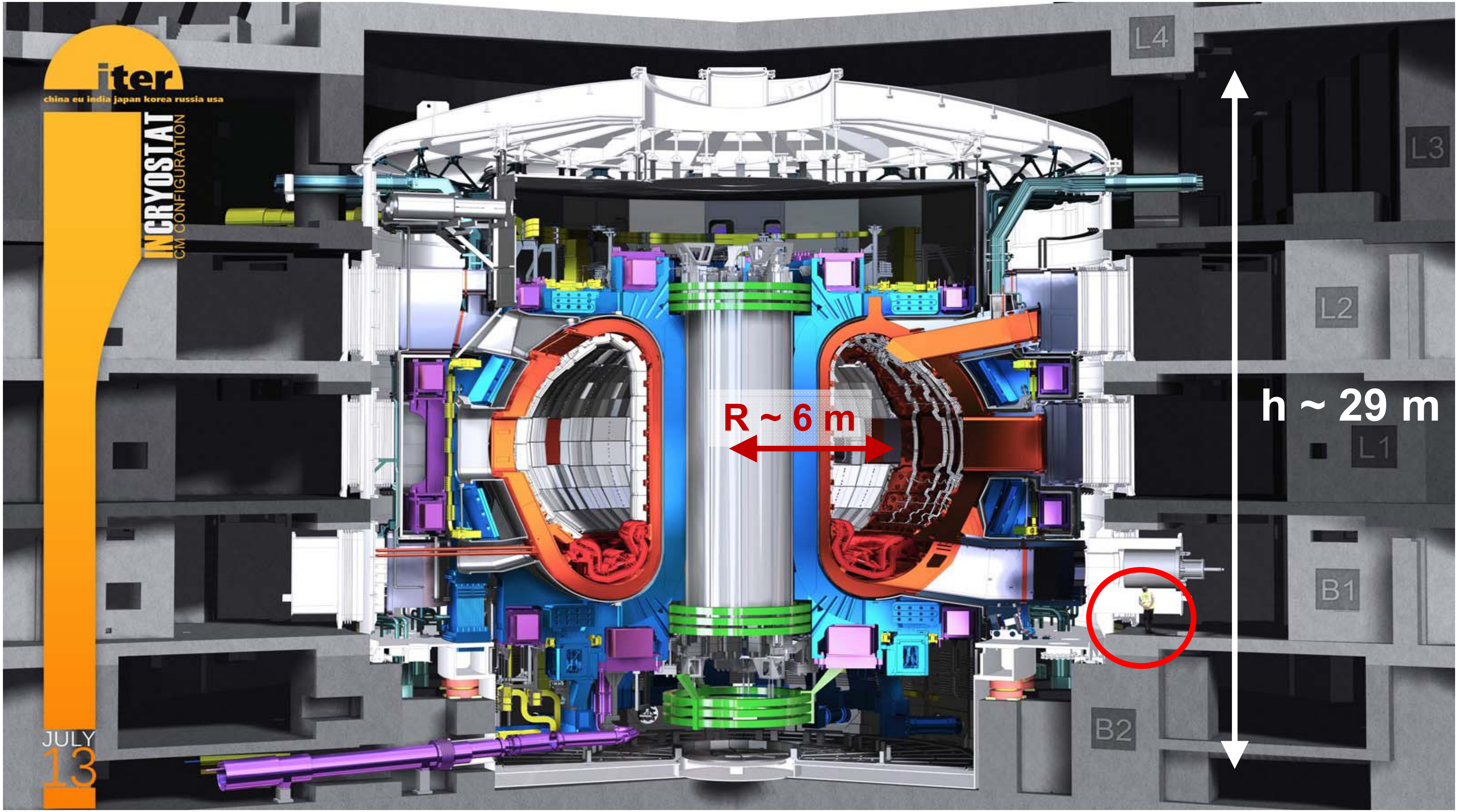


ITER is primarily an experiment but also a major technology test bed

An essential step towards a DEMO reactor

The ITER scale and operational regime

The ITER device



Design goals

1 Physics

- Produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation
- Aim to achieve steady-state operation of a tokamak ($Q = 5$) and retain the possibility of exploring ‘controlled ignition’ ($Q \geq 30$)

2 Technology

- Demonstrate integrated operation of technologies for a fusion power plant
- Test components required for a fusion power plant
- Test concepts for a tritium breeding module

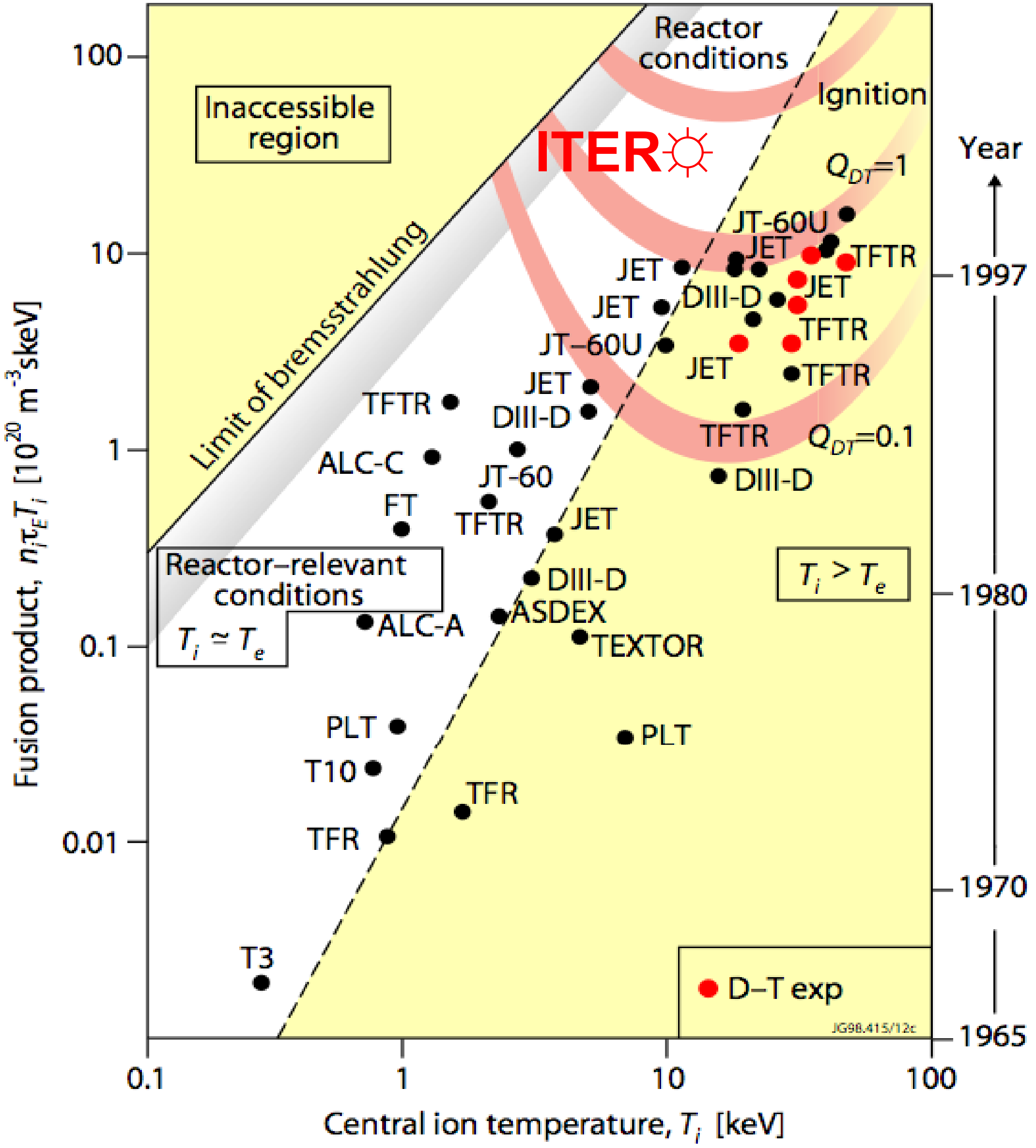
Fusion performance

$$Q = \frac{Fusion\ Power}{Input\ Power}$$

Existing experiments have achieved $nT\tau \sim 1\times10^{21}\ m^{-3}skeV$ and $Q_{DT} \sim 1$

JET and TFTR have produced DT fusion powers >10MW for ~1s

ITER is designed to a scale which should yield $Q_{DT} \geq 10$ at a fusion power of 400 – 500 MW for 300 – 500 s → Baseline scenario

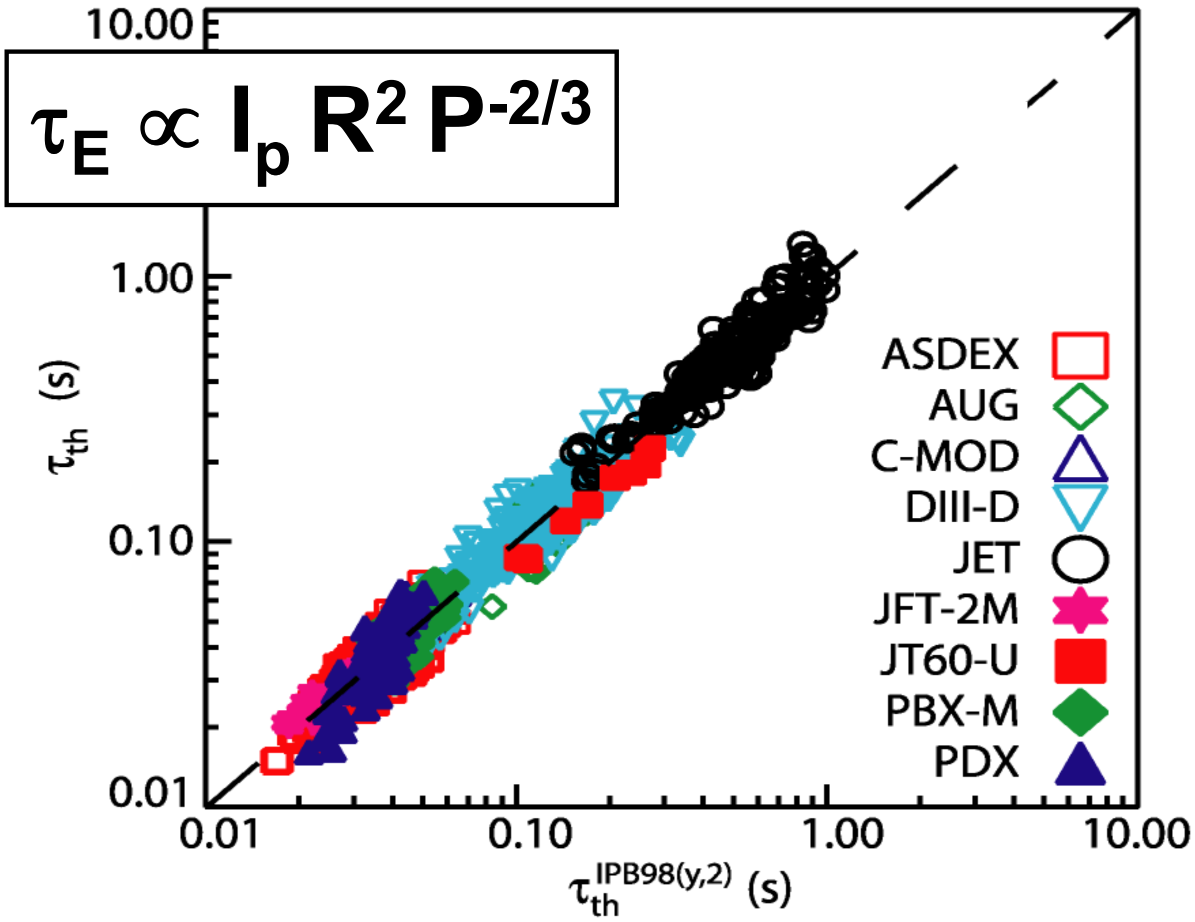


ITER reference scenario for Q =10

Type I ELMing H-mode: robust mode of operation in today's tokamaks

- H-mode (Type-I) confinement is ~2× better than L-mode
  - → in the ITER design, Q=10 in L-mode not possible

IPB98(y,2) TYPE-I ELMing H-MODE SCALING FROM EXPERIMENT



How is ITER different for physics & tokamak operation?

Burning plasma: self-heated by α-particles

- non-linearity in total heating power due to dependence on plasma profiles
- MHD: sawtooth stabilisation by α-particles, fast particle modes

Plasma control (position, shape, fuelling, heating, stability, exhaust)

- time constant for position control is >1s → very easy to damage plasma-facing components (e.g. on inner wall of vacuum chamber)
- very complex control matrix

Very high stored energy

- disruptions, ELMs, melting of metallic PFCs

High plasma current (15 MA for Baseline Q = 10 scenario)

- runaway electron damage of PFCs, huge disruption forces

High ion fluence (integrated plasma flux) to PFCs

- erosion of PFCs and migration of wall material, dust formation

How is ITER different for physics & tokamak operation?

Routine operation at Q = 10 (hopefully!) → means operating near design limits

- ITER can regularly exceed the technological limits of actively cooled PFCs
- Extremely robust machine protection system mandatory

Nuclear operation (tritium and neutrons)

- retention of tritium on PFCs
- tritium reprocessing
- tritium breeding test blanket modules (TBMs)
- remote handling is required for 100% of in-vessel work during the nuclear phase
- dust inventory
- (diagnostic design)
- (TF coil heating)
- LICENSING

ITER licensing process

In December 2010, the ITER safety files were formally accepted by the French Authorities

- Enabled technical evaluation by the Nuclear Safety Regulator (ASN) as well as the public evaluation of the files

The Public Enquiry was conducted from 15th June to 4th August 2011.

On 19th September 2011, the Inquiry Commission officially 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

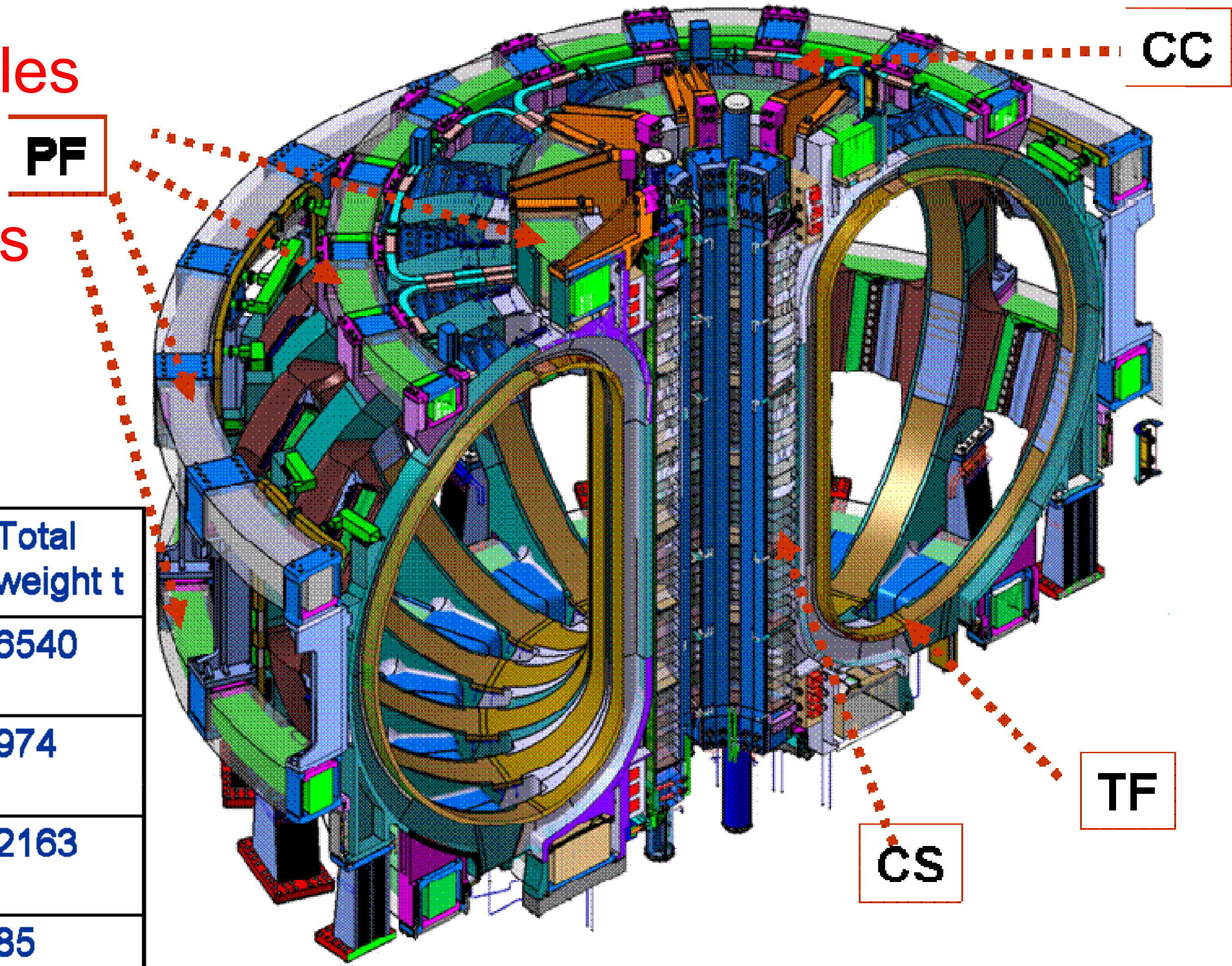
A LA POURSUITE DU PROCESSUS D'AUTORISATION DE CREATION DE L'INB ITER

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

- ITER is now formally a Nuclear Operator: INB no. 174

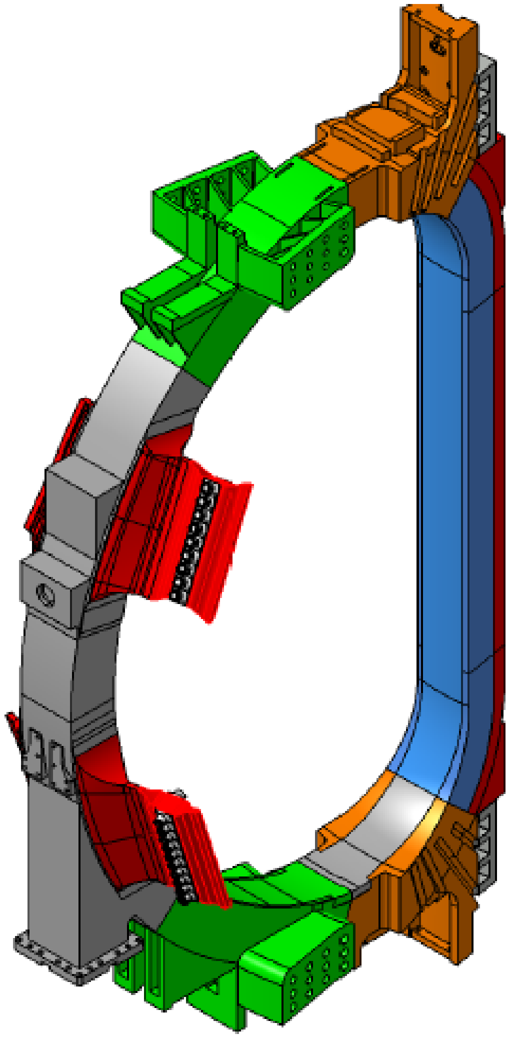
ITER - Magnet Systems

48 superconducting 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

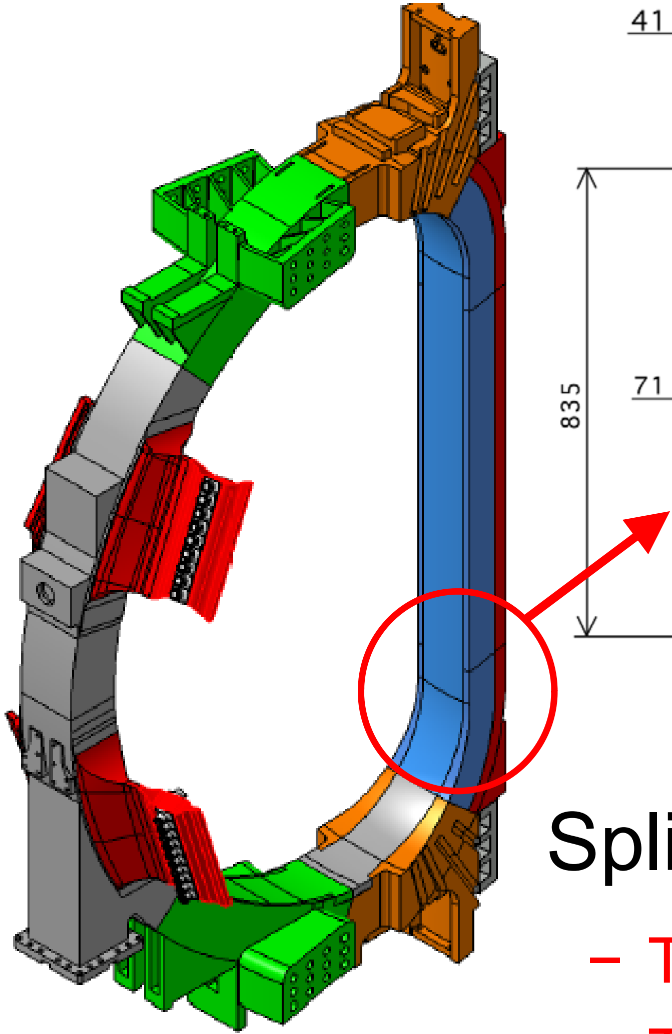
Toroidal field coils

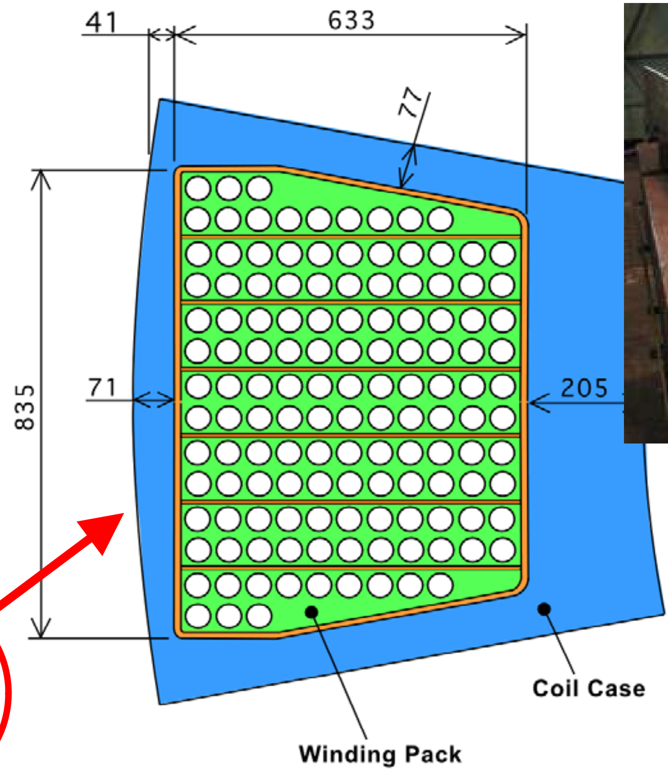


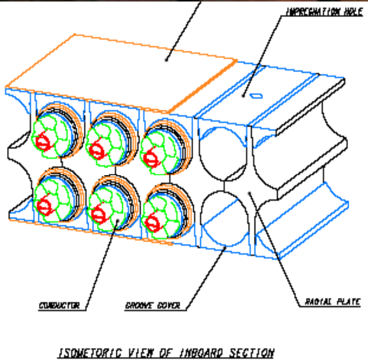
16 x 9 m, **~360 t**
(EU, JA – 18 coils)

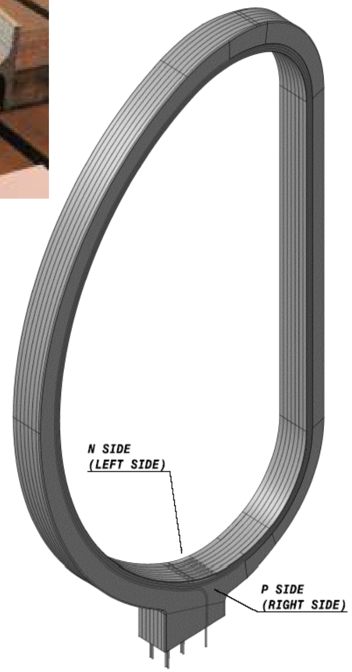
Boeing 747-300
(maximum take-off weight **~377 t**)

Toroidal field coils





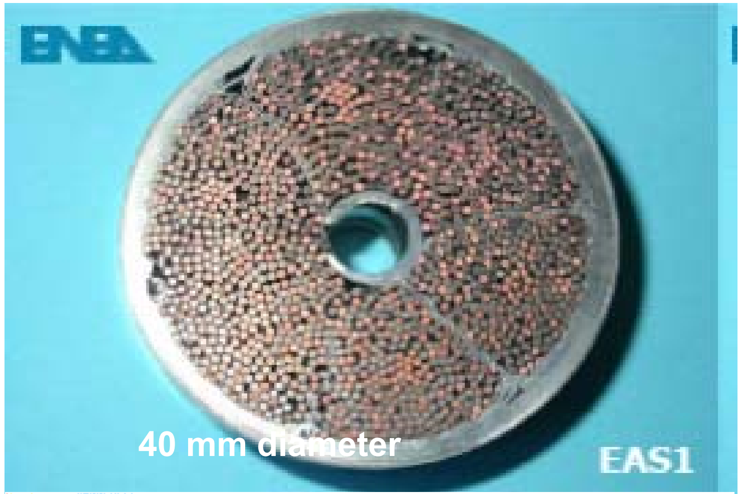


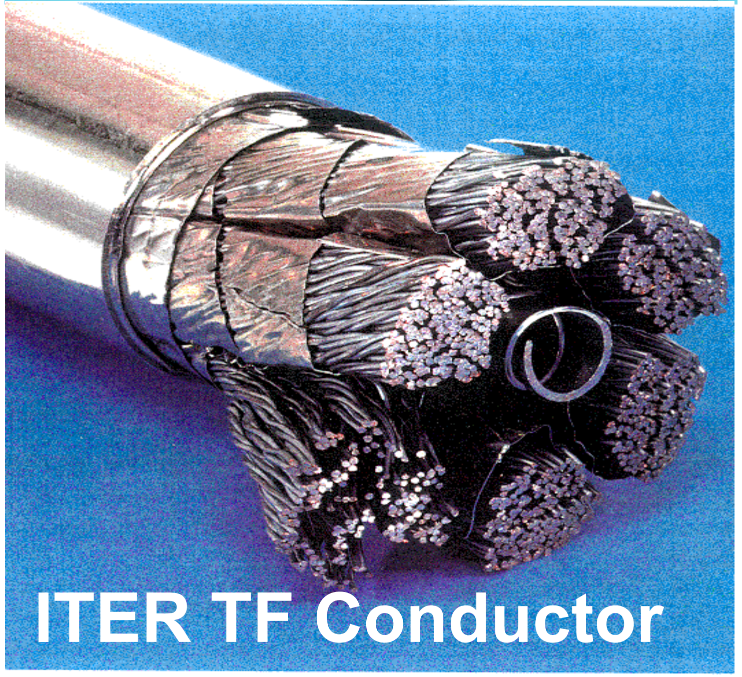


Split into 3 main production areas

- TF-conductors (EU, JA, RF, CN, KO, US)
- TF structures: 4500t of high precision stainless steel forgings and plates, assembled by welding
- TF windings and coils (EU, JA)

Superconductor procurement





Facts

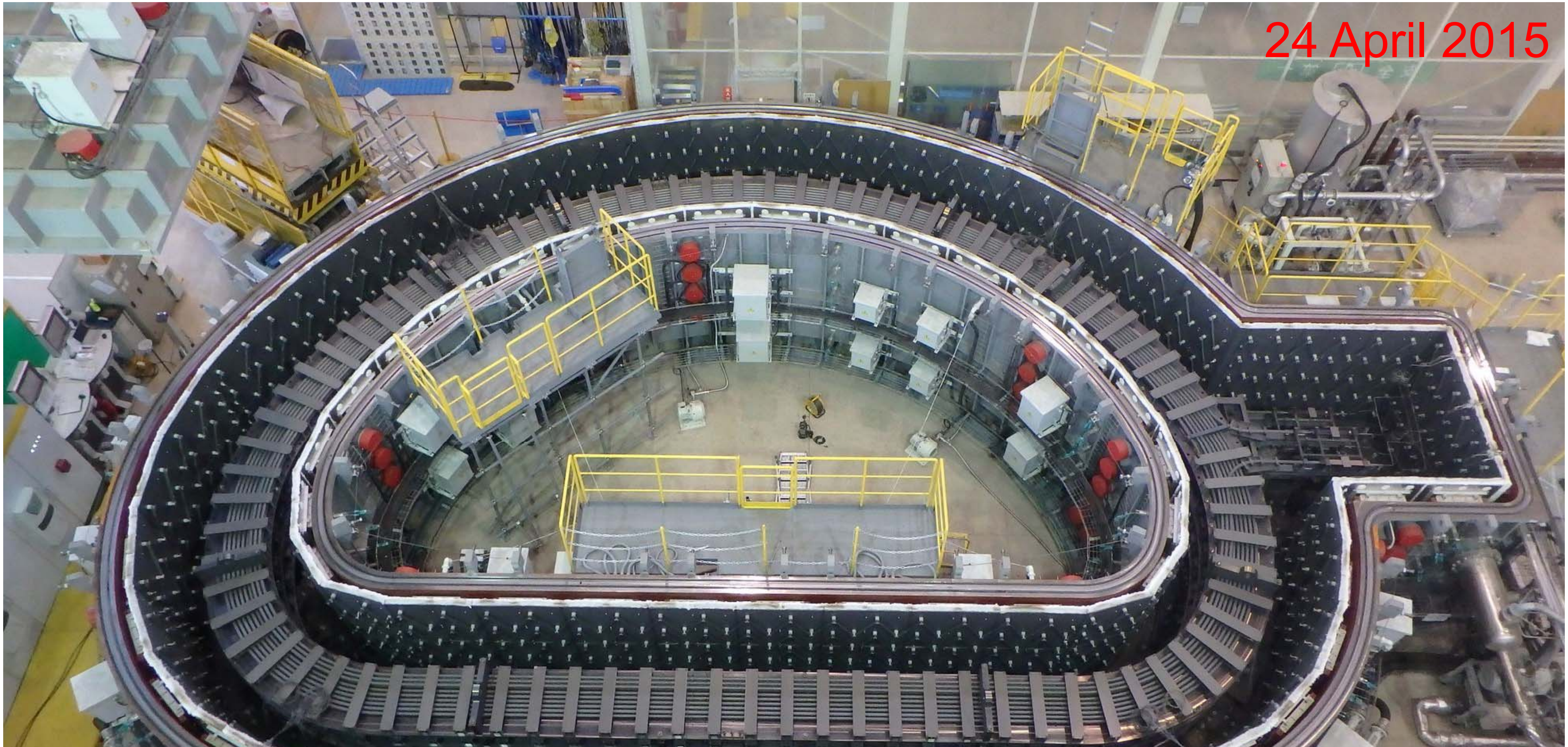
- Procurement underway since 2008 ~100,000 km / 500 tonnes of Nb_3Sn strand for TF and CS magnets
- Pre-ITER world production was ~15 t /year → 100 t /year for ITER
- 11 suppliers from 6 Domestic Agencies
- 200 km of cable in conduit, 2800 t
- Almost all conductor unit lengths now accepted by the IO
- Estimated total value ~€610 million

Toroidal field coil radial plates

The radial plates that hold the conductor of the toroidal field coils are very complex, D-shaped stainless steel structures with grooves machined on both sides along a spiral trajectory.

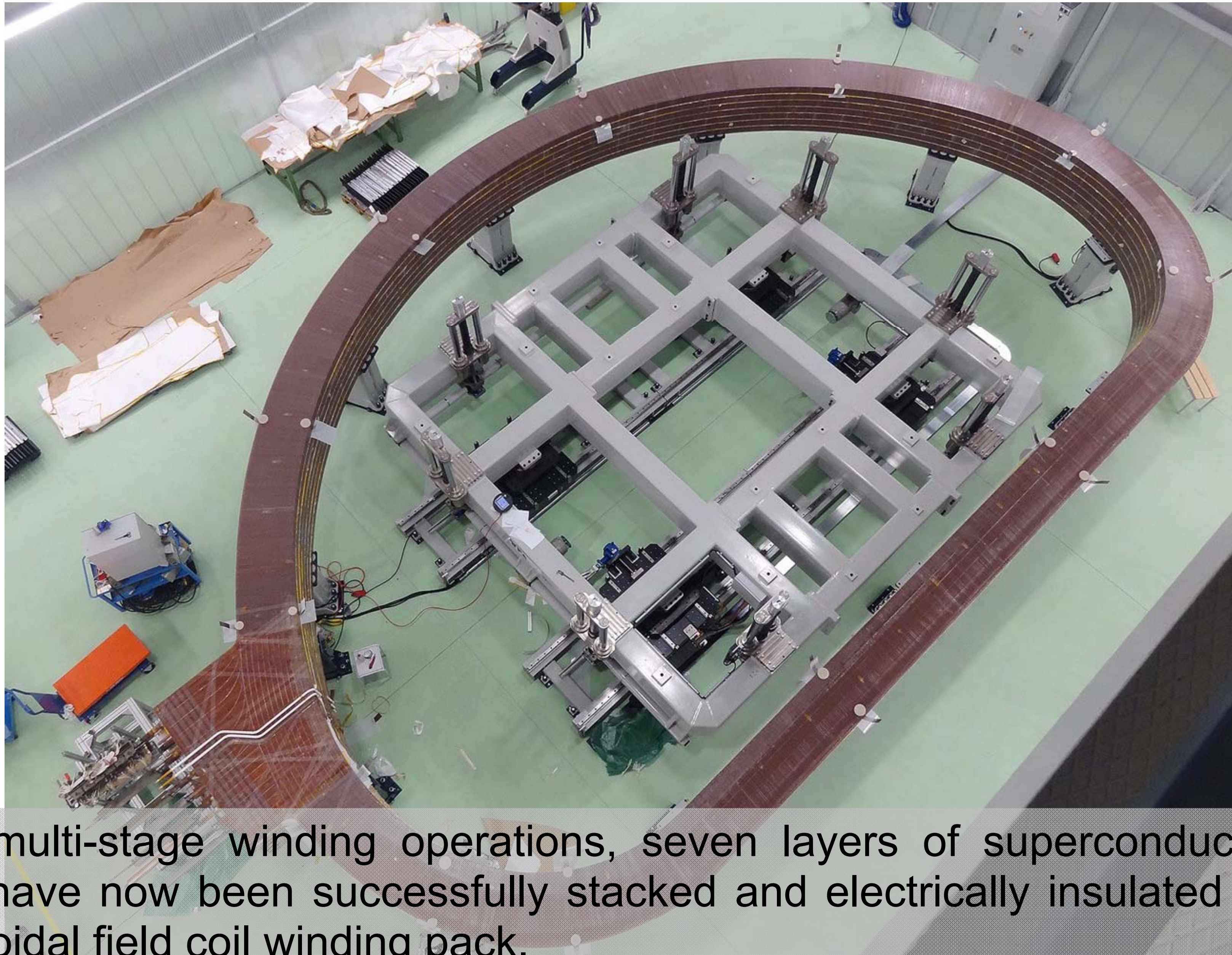
SIMIC in Camerana, Italy, September 2011

Toroidal field coil furnace in Japan



TF coil windings are heat treated at 650°C for 100 hours to react tin and niobium to form the superconducting compound Nb_3Sn. Japan's share of toroidal field windings are treated in this furnace at Mitsubishi Heavy Industry's Futami factory.

First EU TF coil winding pack



26 February 2016

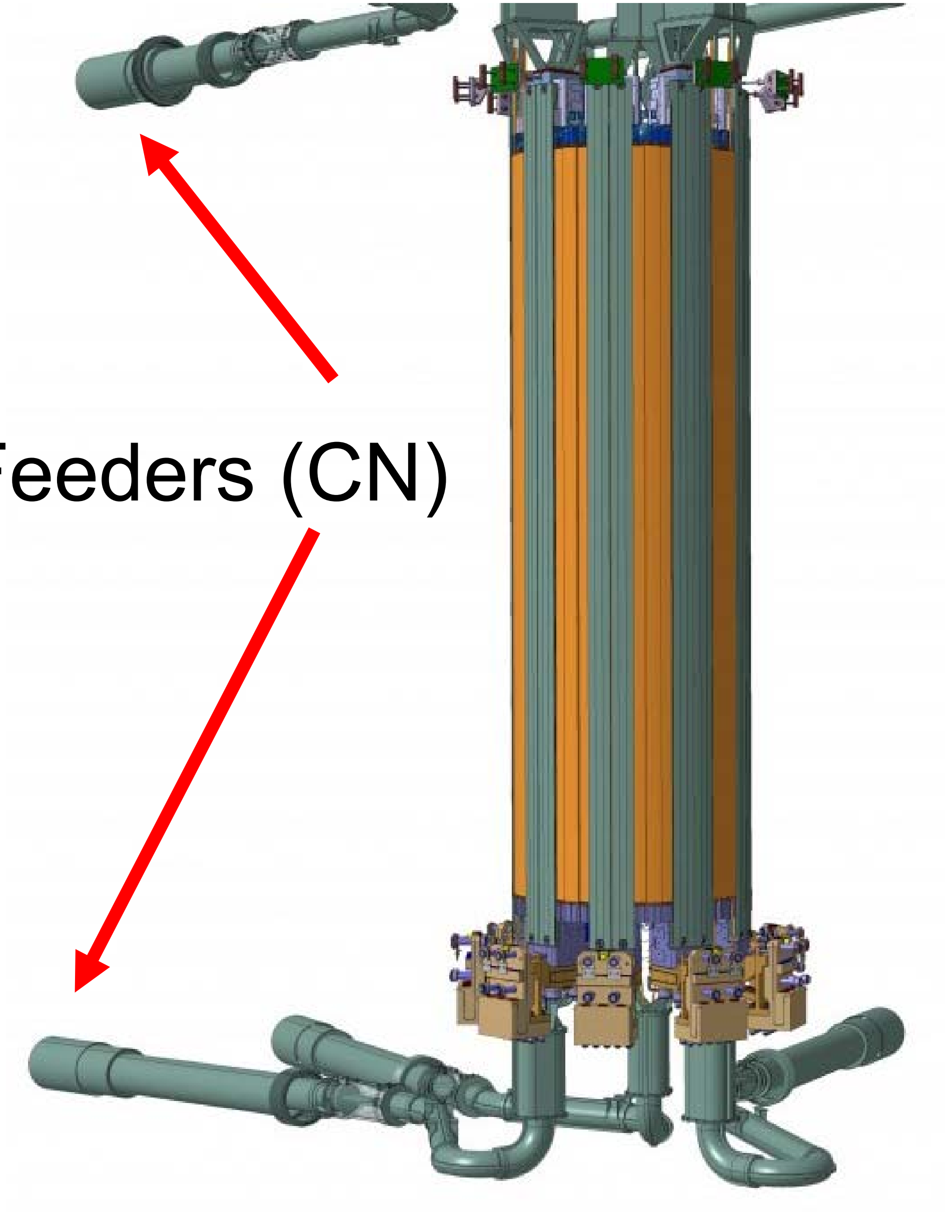
Following multi-stage winding operations, seven layers of superconducting double pancakes have now been successfully stacked and electrically insulated to form the first EU toroidal field coil winding pack.

First EU TF coil winding pack

8 April 2016

After vacuum-pressure insulation and testing, the final seven-layer pack ready for installation into its stainless steel case.

Central Solenoid

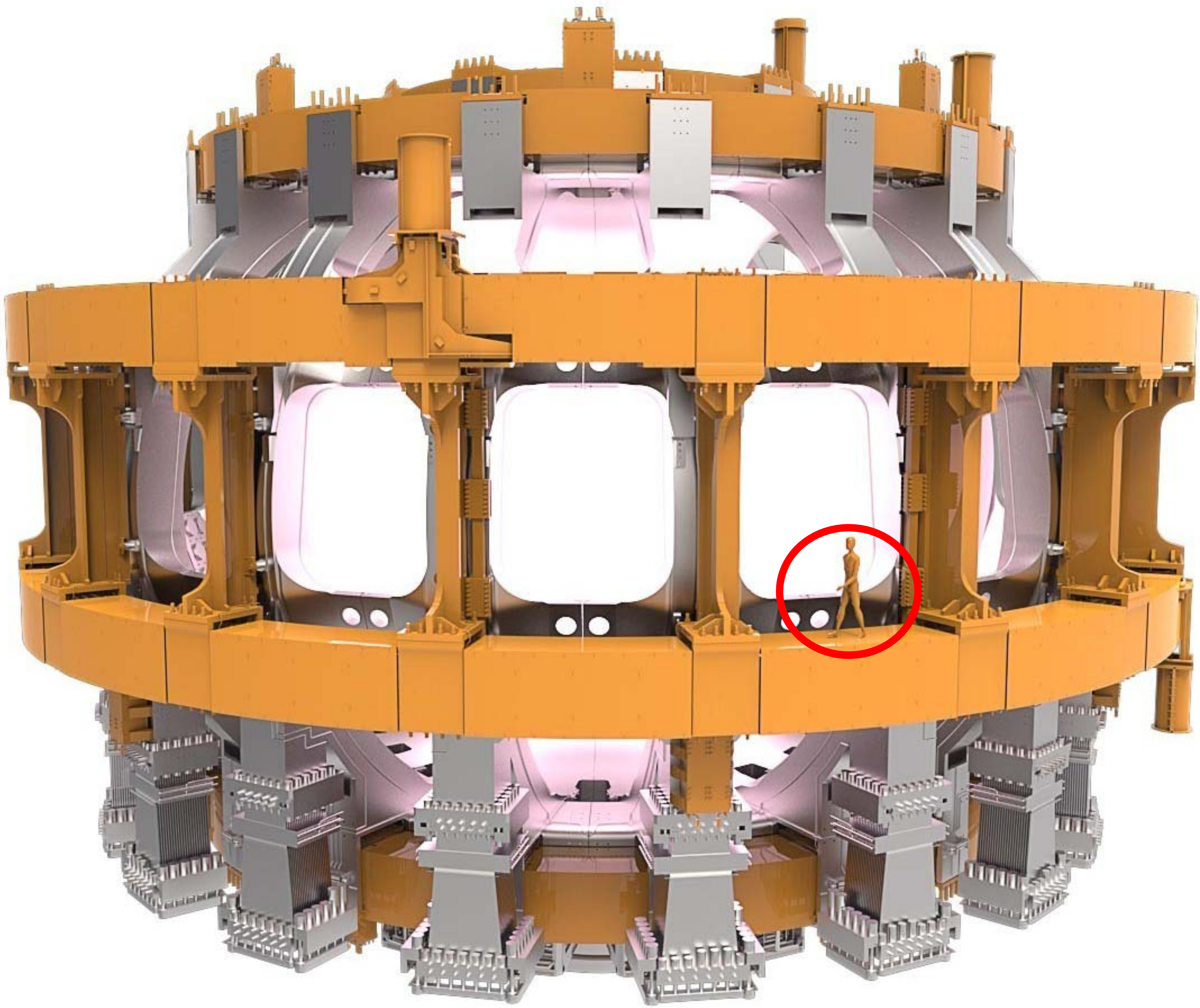


Feeders (CN)

CS Coil Stack (US)

- 6 independently powered modules
- 12m tall x 4m diameter
- Nb_3Sn conductor
- 13T (peak field)
- 45kA (peak current)
- 1000 t

Poloidal Field Coils



- 6 coils (EU, RF, CN)
- NbTi conductor
- 6.8 T (peak PF field)
- 55 kA (peak current)
- PF2-6, manufactured on-site
- PF3: 24.5 m diameter, 386 t
- PA for PF2-6 signed with EU
- PA for PF1 signed with RF in March 2011
- PF6 being manufactured by CN

PF coils #1 and #6 manufactured off-site

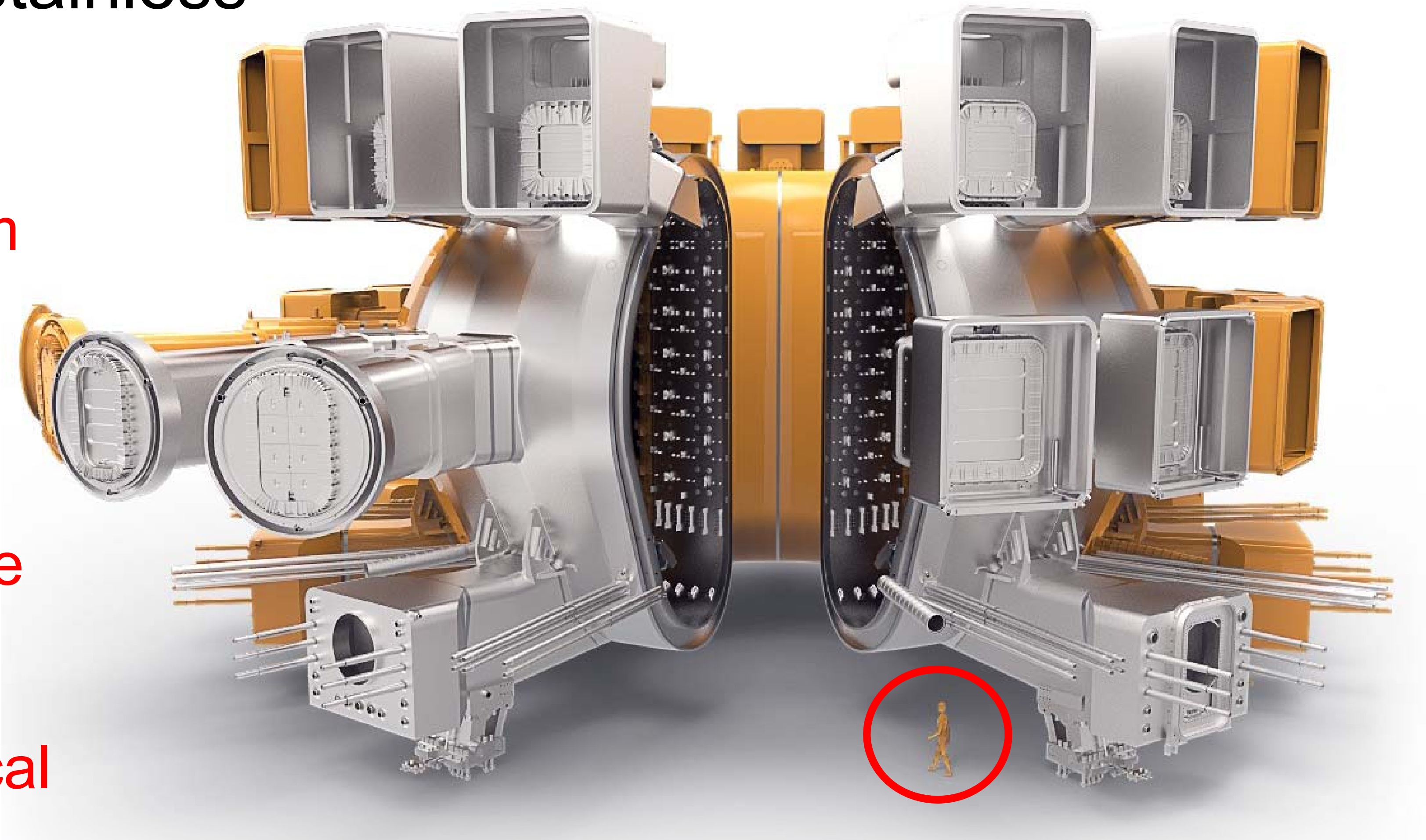
23 October 2015

The first of 8 winding packs for PF coil #1 undergoing epoxy impregnation at the Srednenevsky Shipbuilding Plant in Saint Petersburg, Russia

Vacuum Vessel

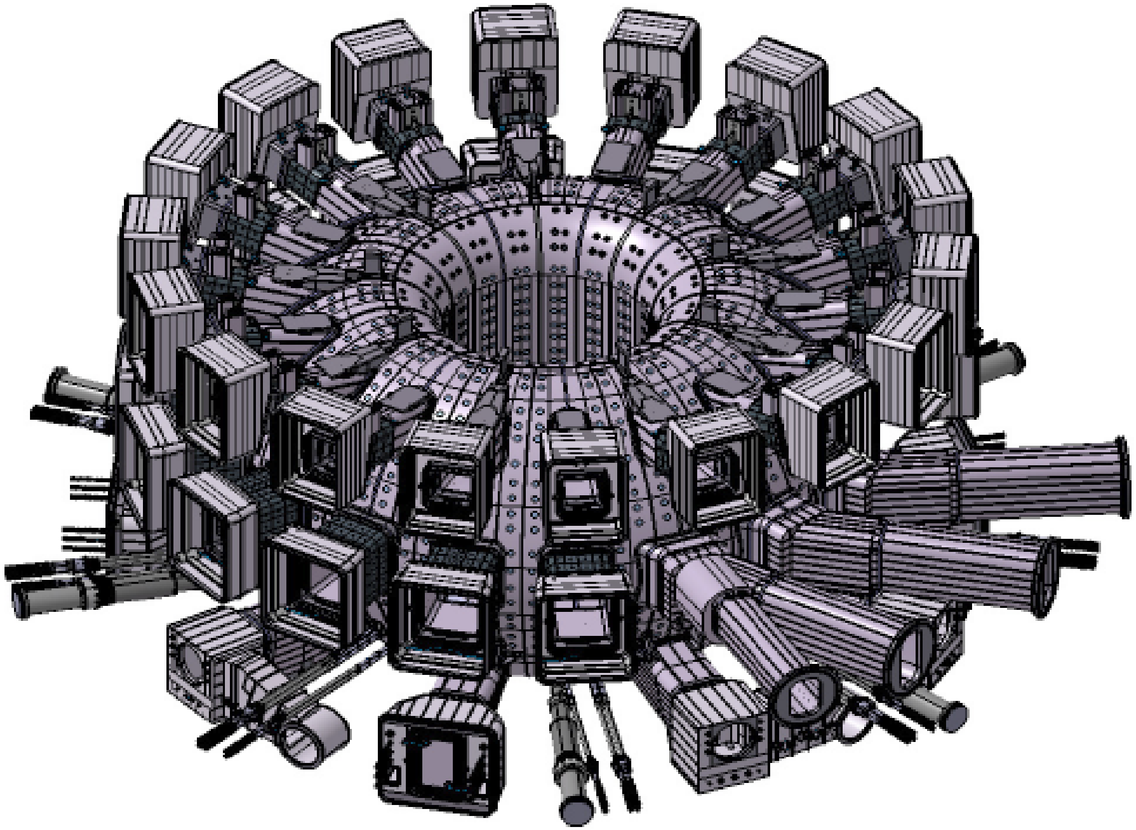
Double-walled, stainless steel structure

- 19.4m outer diameter, 11.3 m height, SS 316 L(N)-IG, 5300 t
- Primary tritium containment barrier, bakeable to 200ºC
- Must withstand enormous vertical forces during disruptions

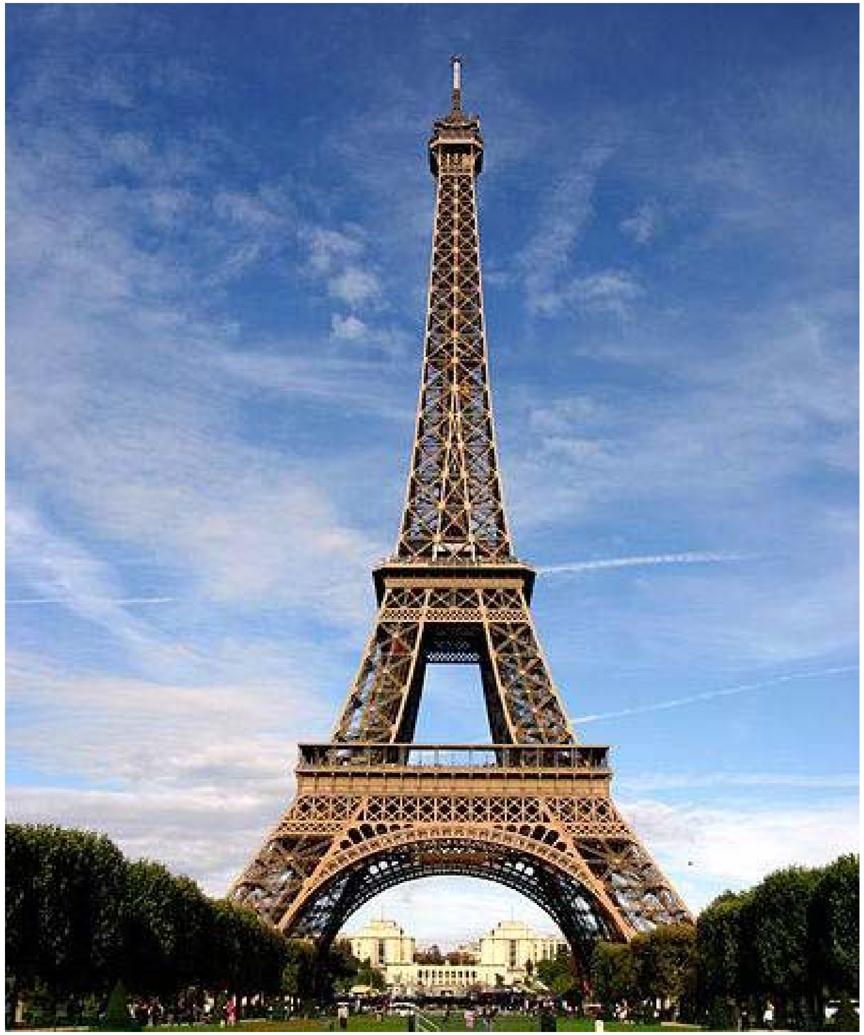


Nominal base pressure ~5 x 10^{-8} mbar

Vacuum Vessel



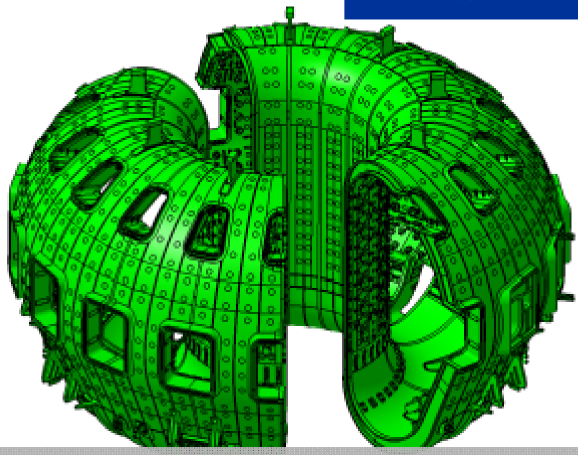
Weighs about 25% less than the Eiffel Tower (more with in-vessel components included)



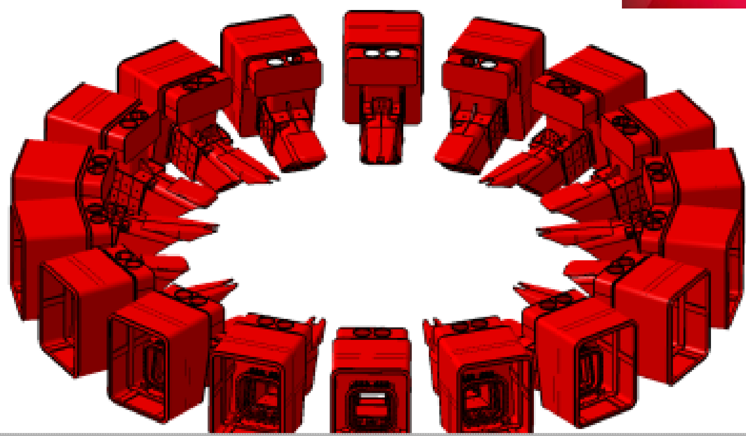
7300 t
324 m tall

Vacuum vessel procurement

5 sectors of VV

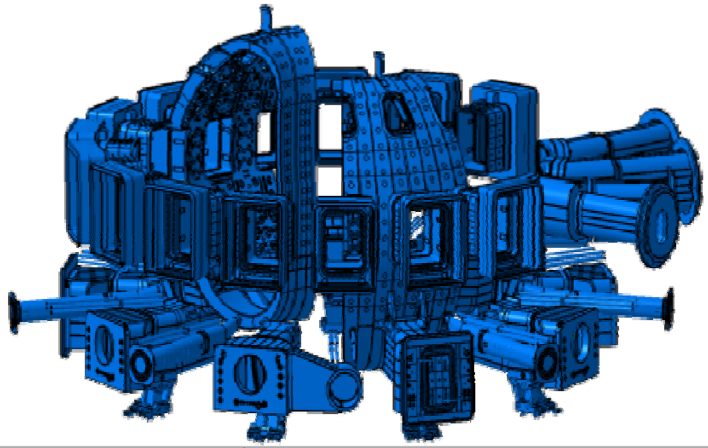


18 upper ports

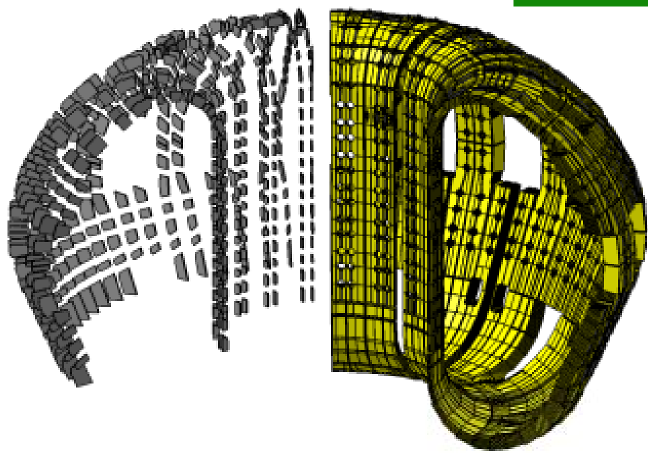


234.28 kIUA: 8% of total in kind cost of the ITER machine

4 sectors of VV
17 Eq. & 9 lower ports



Inner wall shield/ribs

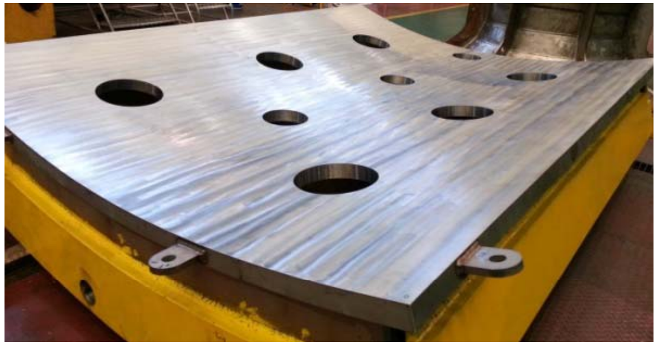


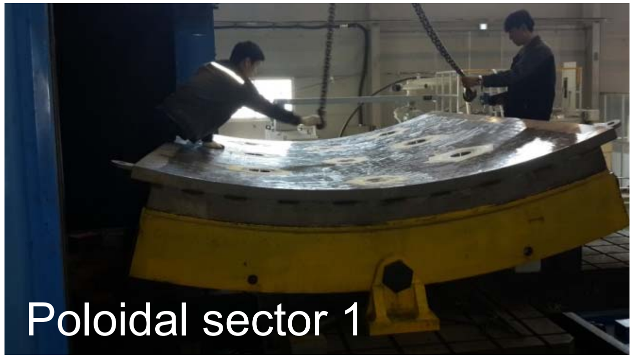
Prototypes and manufacture underway

Forging of steel and forming

Prototypes and manufacture underway

Forging of steel and forming, manufacture of Sector #6 and lower ports





Poloidal sector 1

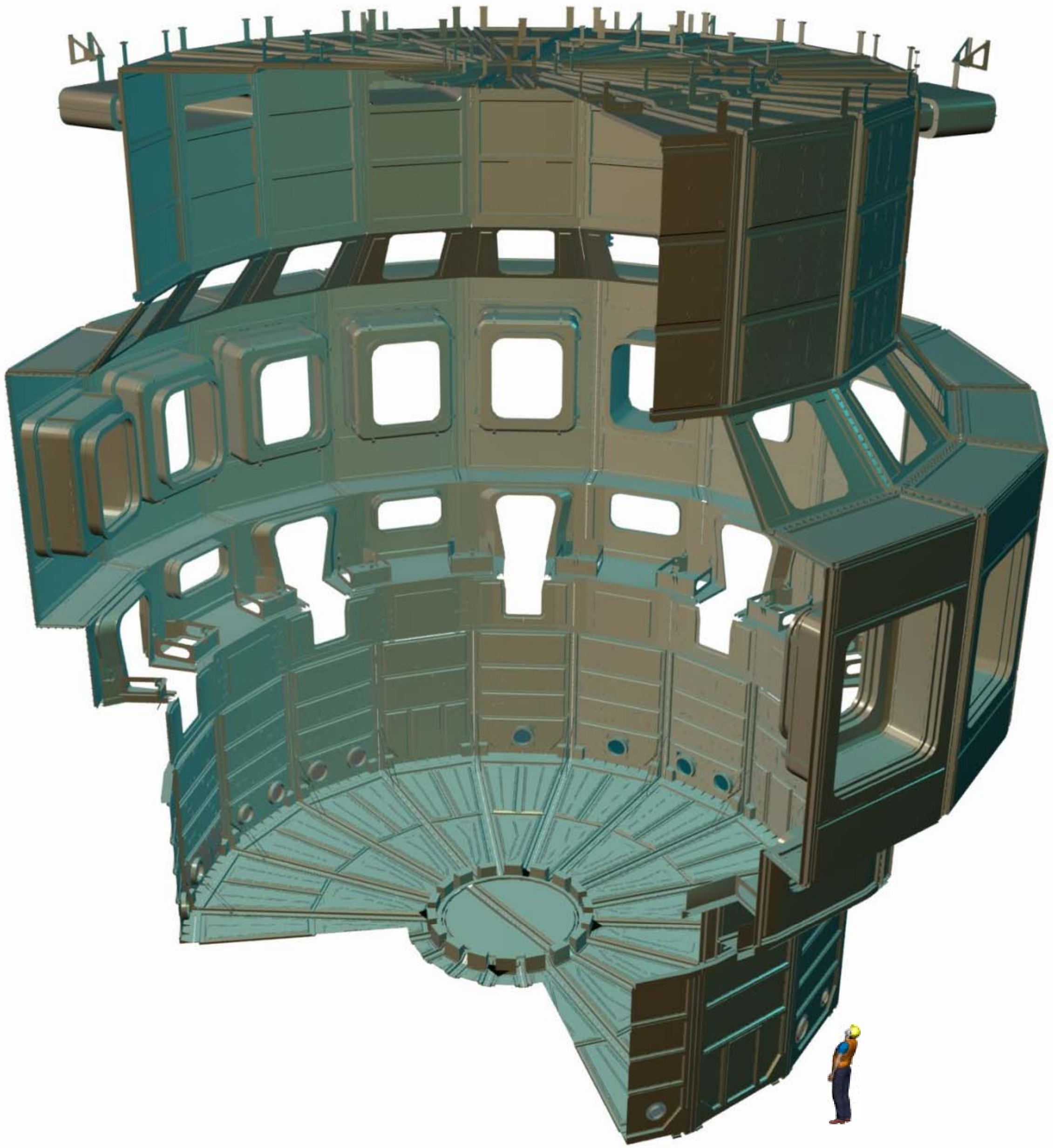
Poloidal sector 3

Lower port stub extension welding

Poloidal sector 2

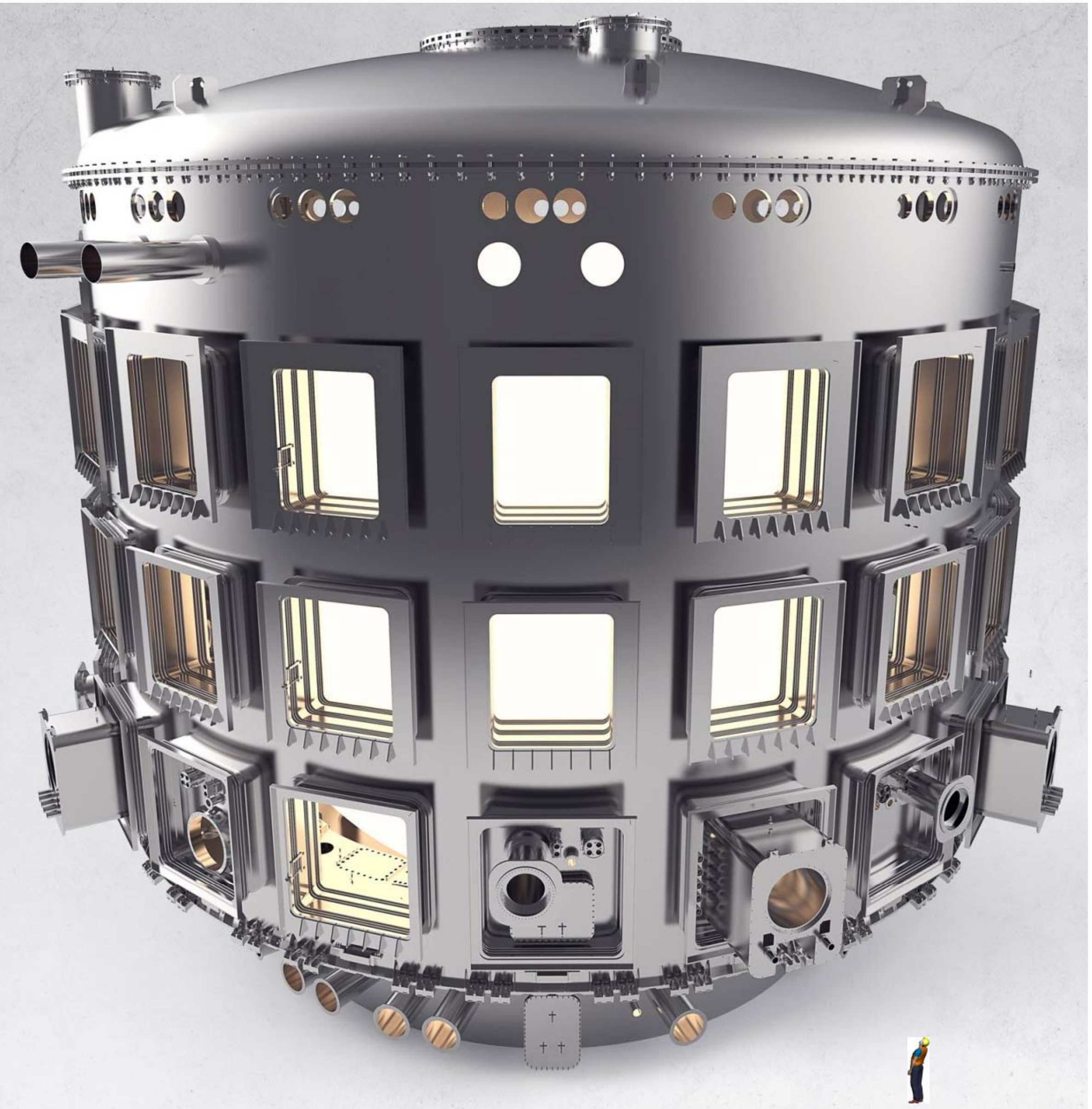
Poloidal sector 4

Main inner heat shield



- Provides barrier for thermal loads from warm components to the superconducting coils (4.5K)
- Operates at 80 K (gaseous He in cooling pipes)
- Stainless steel panels are silver coated to reduce emissivity
- Mass: ~1000 t
- A smaller shield isolates the TF coils from the vacuum vessel

ITER Cryostat: vacuum insulation for SC coils



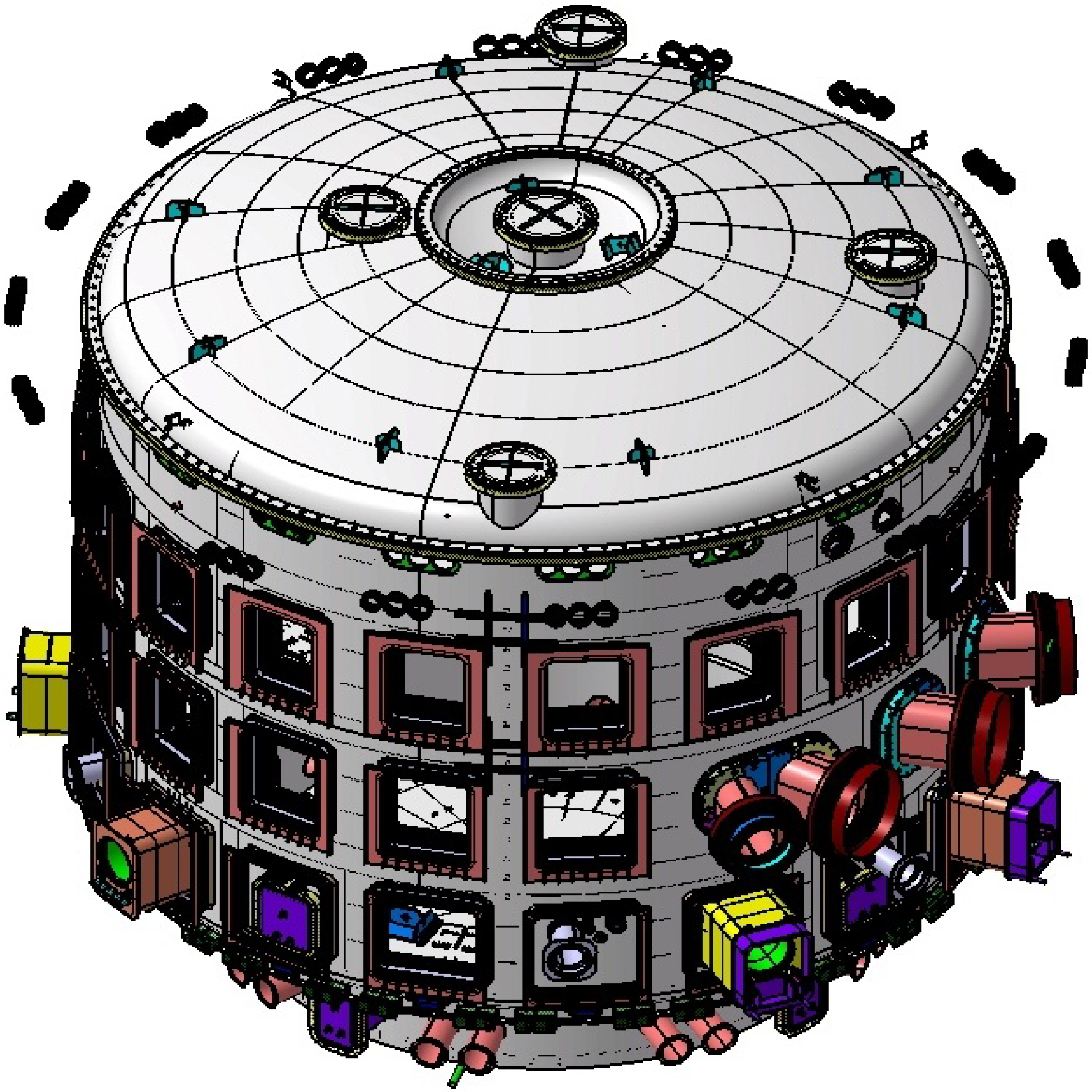
Outer thermal shield

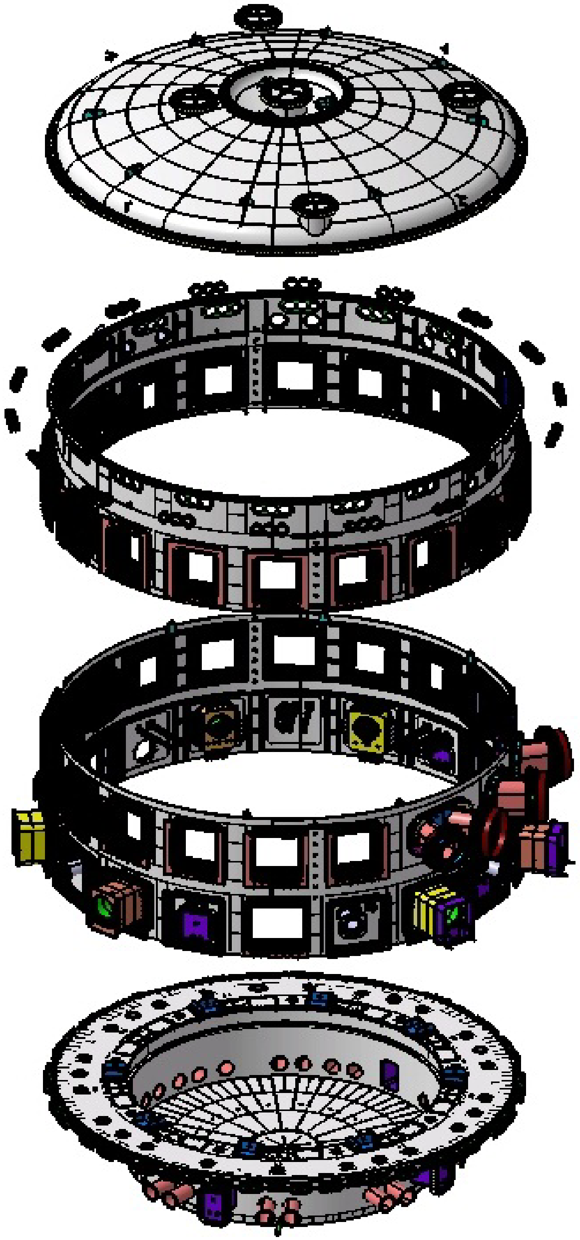
- Diameter: 29.4 m
- Height: ~29 m
- Mass: ~3500 t
- Base pressure <10^{-4} mbar
- Stainless steel 40 – 180 mm thick

IN-DA manufacturing

- Contract signed with L&T Ltd on 17 August 2012
- Being dispatched in 54 modules to ITER

ITER Cryostat





Top lid

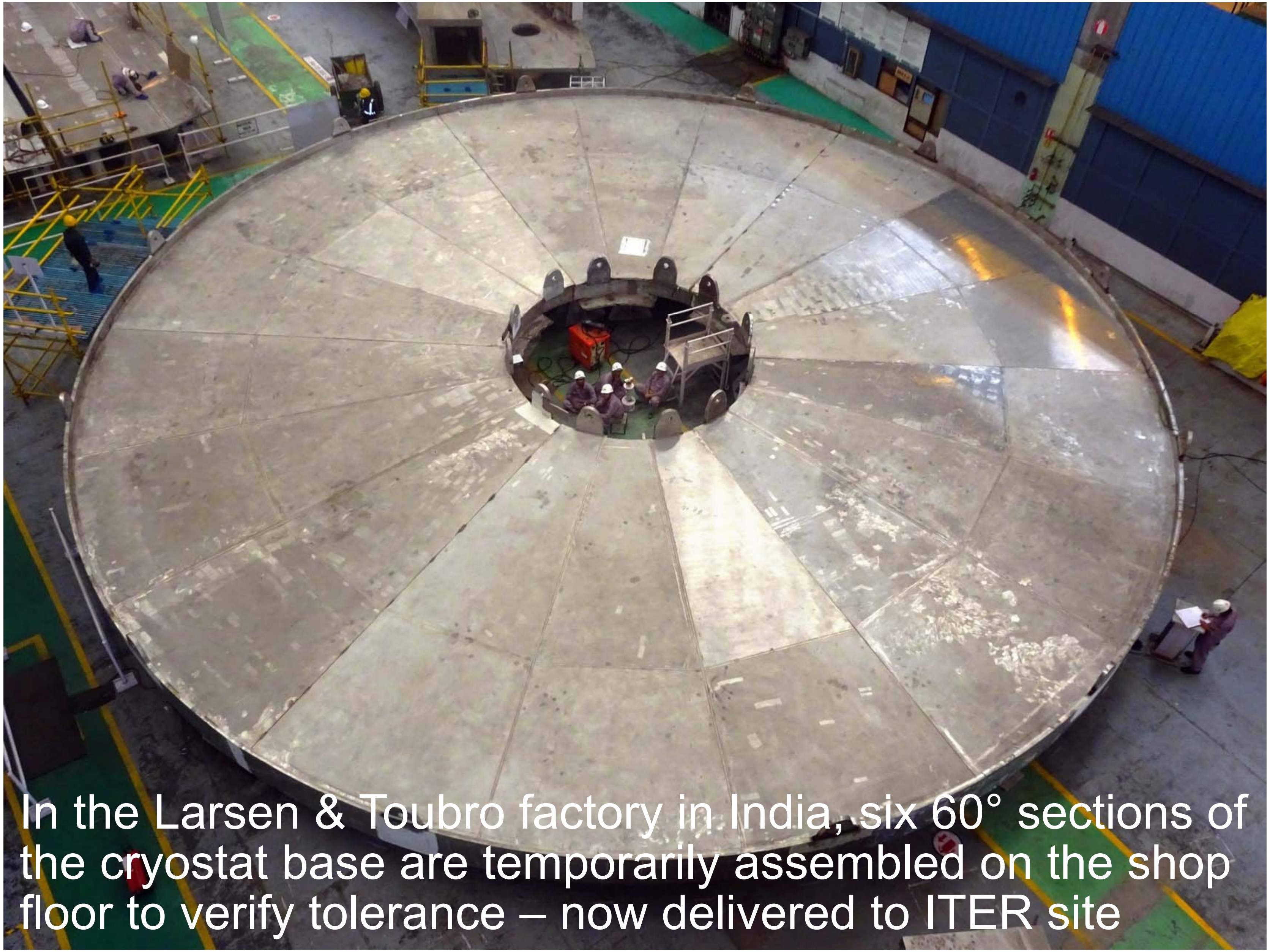
Upper cylinder

Lower cylinder

Base section

Transfers loads to tokamak floor

Cryostat base already complete

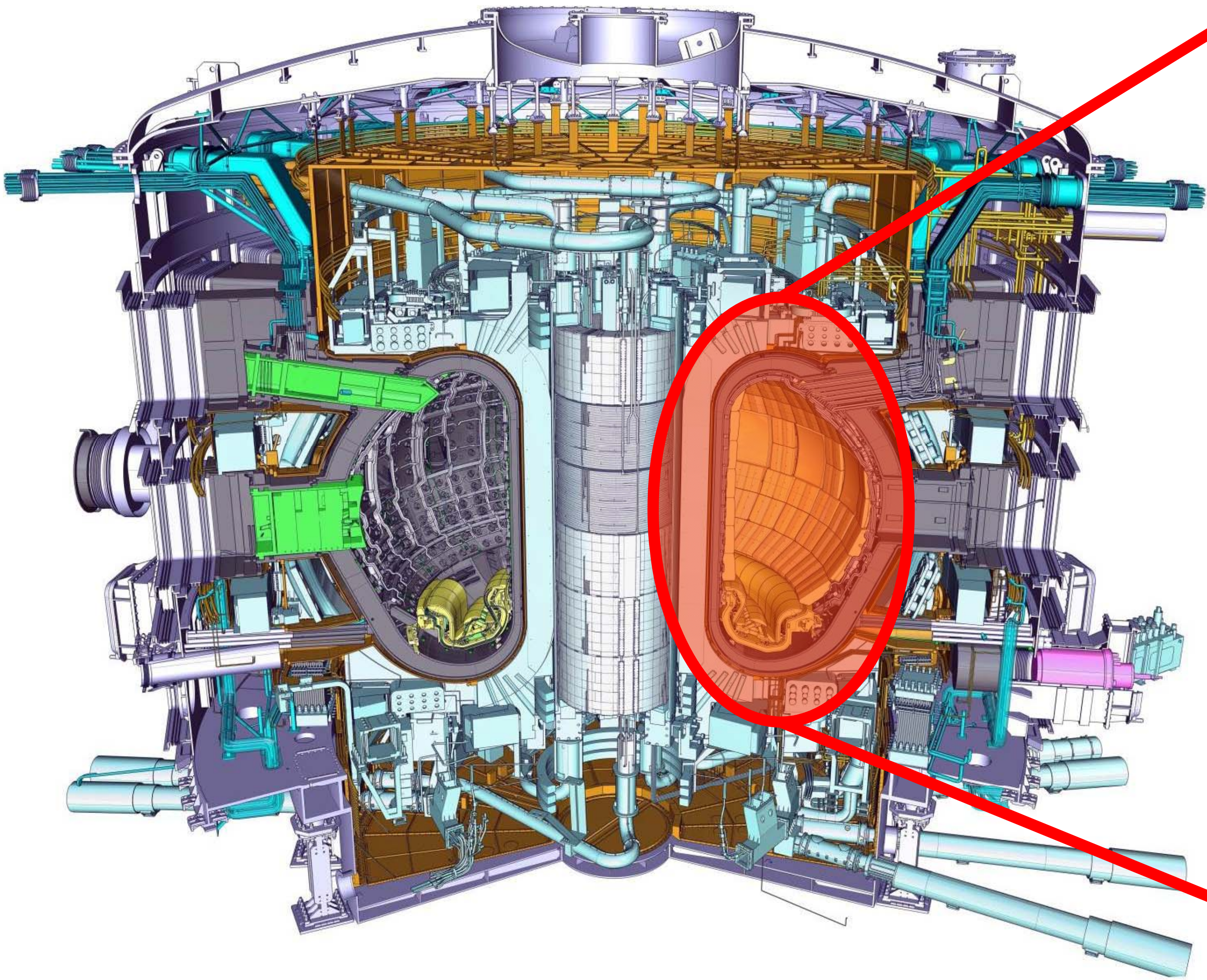


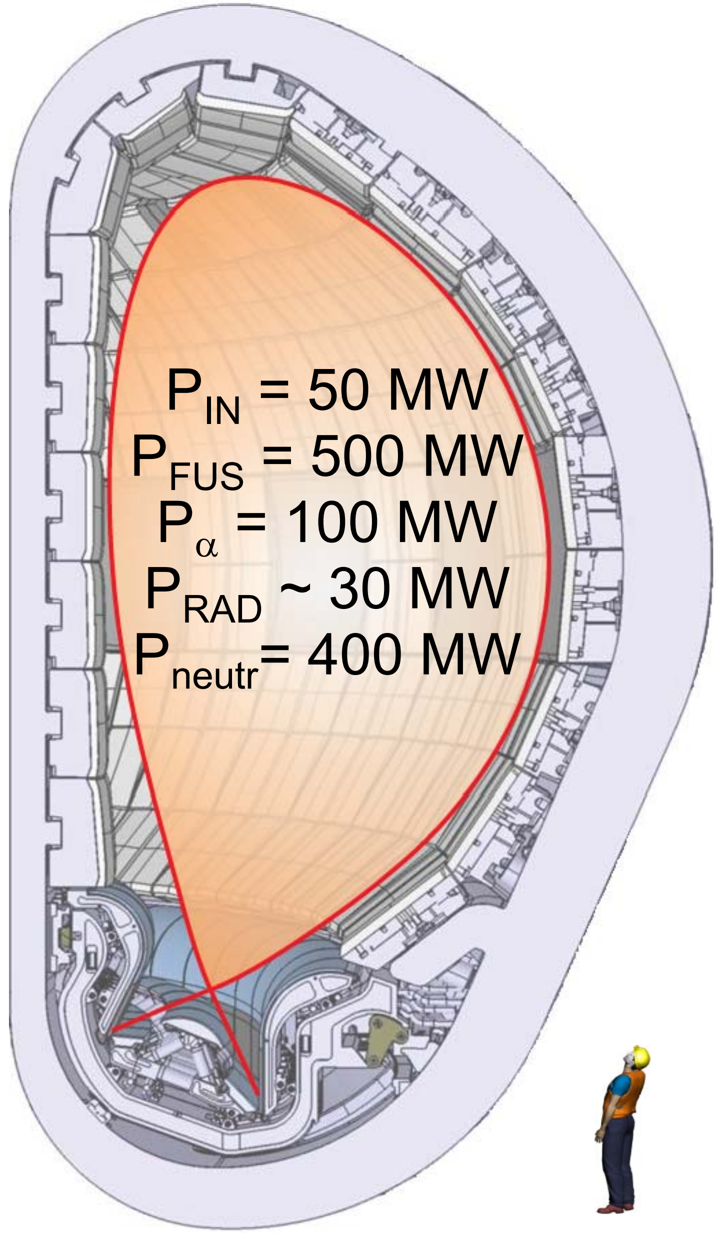
In the Larsen & Toubro factory in India, six 60° sections of the cryostat base are temporarily assembled on the shop floor to verify tolerance – now delivered to ITER site

July 2015

ITER burning plasma power exhaust

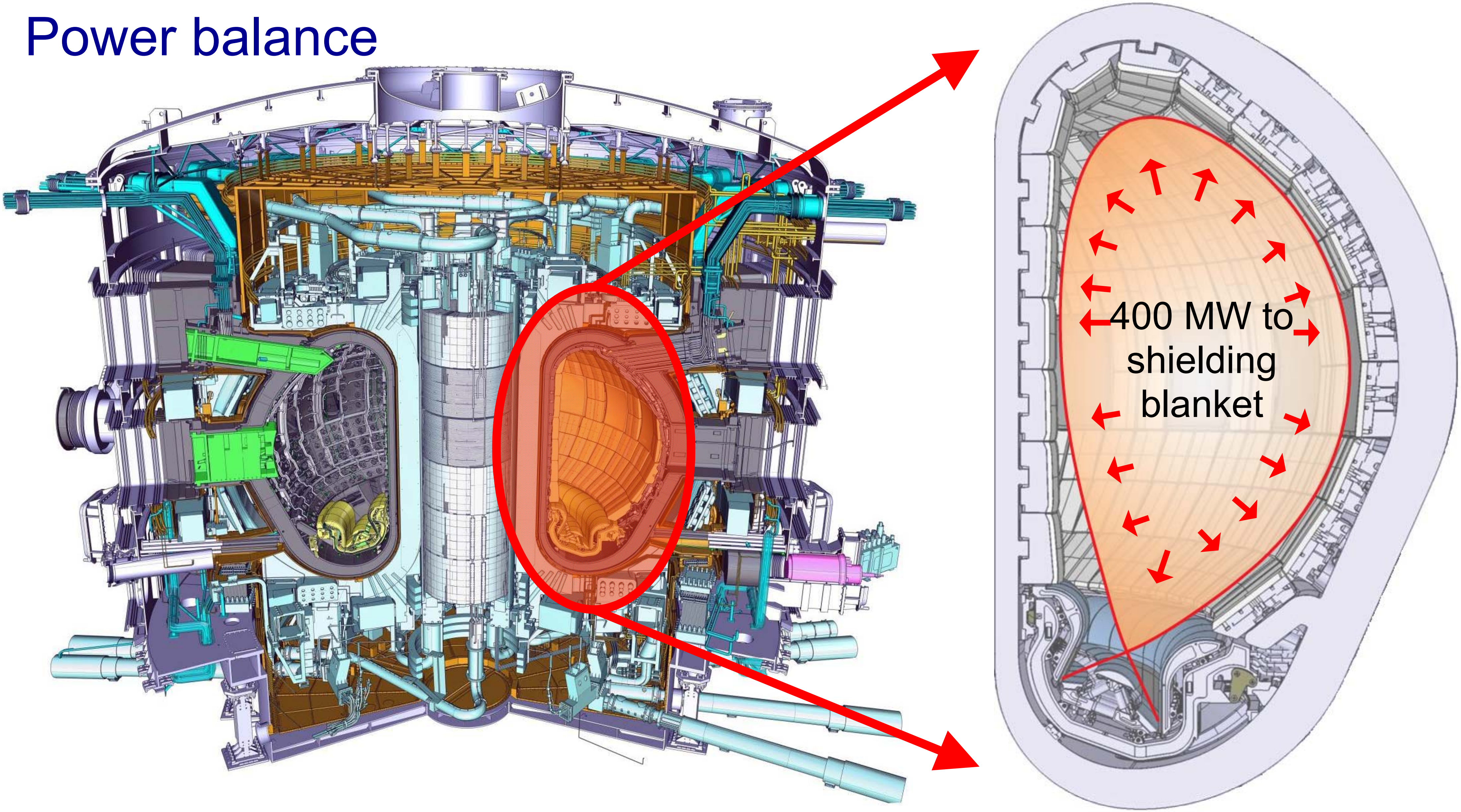
Power balance





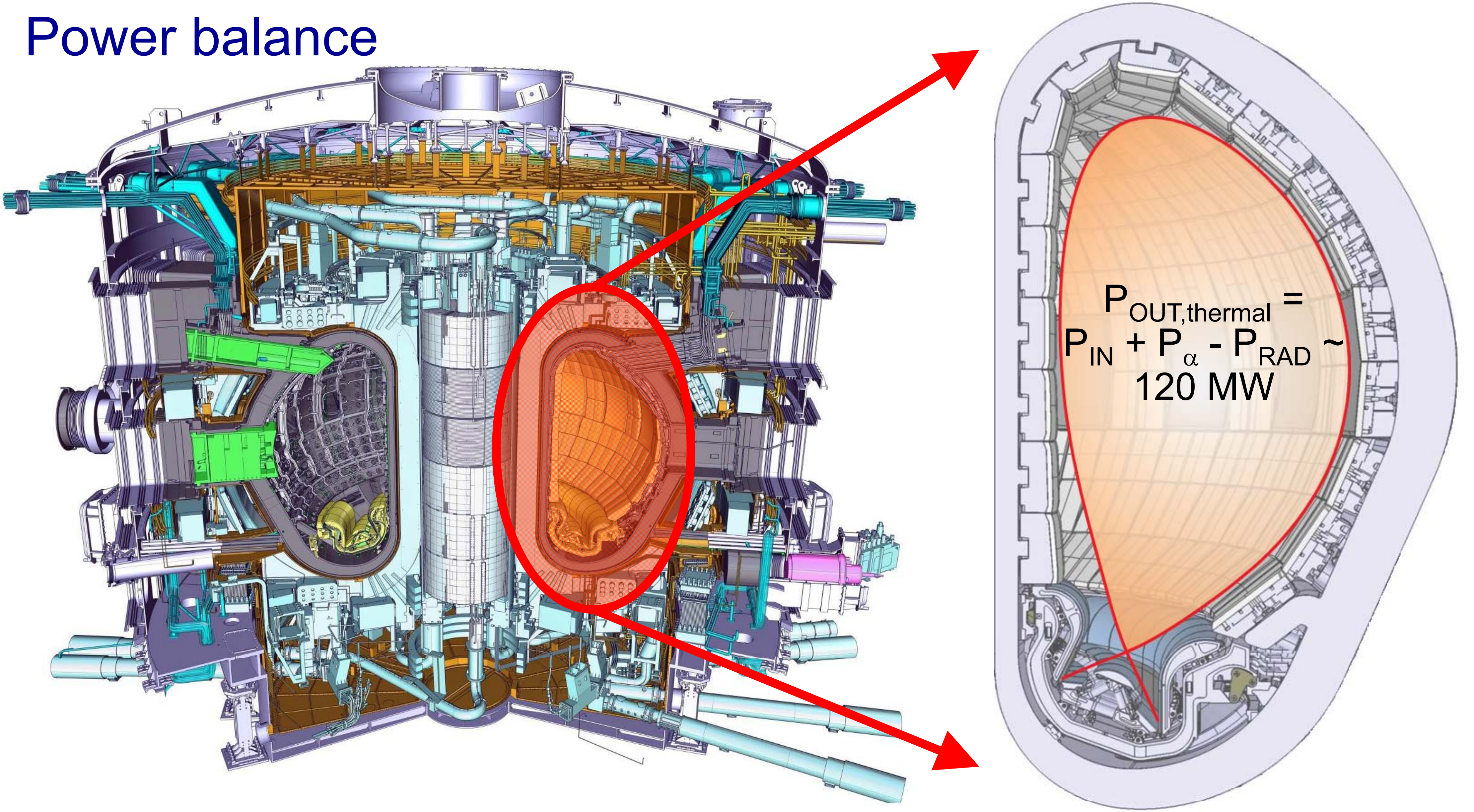
ITER burning plasma power exhaust

Power balance



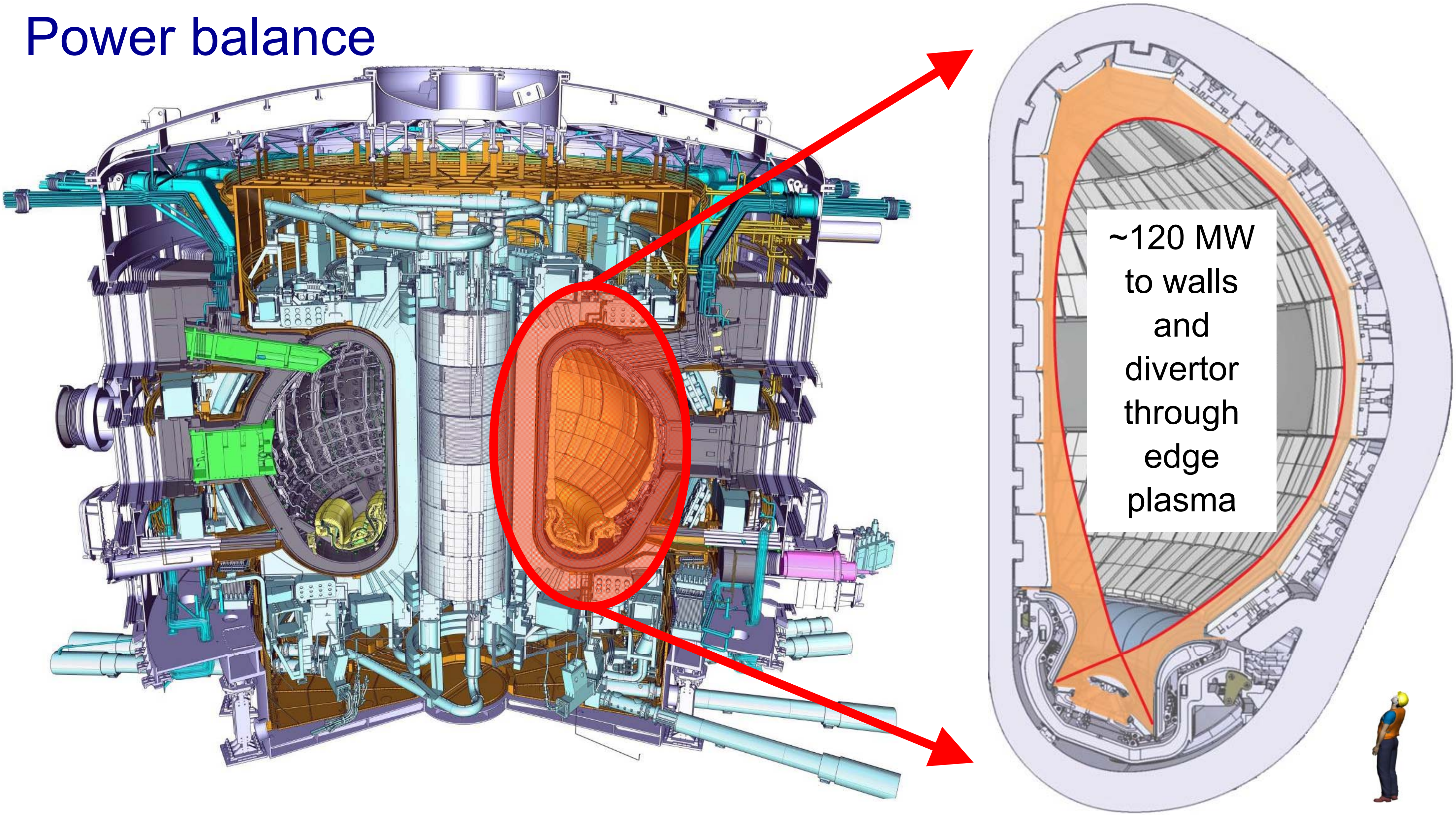
ITER burning plasma power exhaust

Power balance



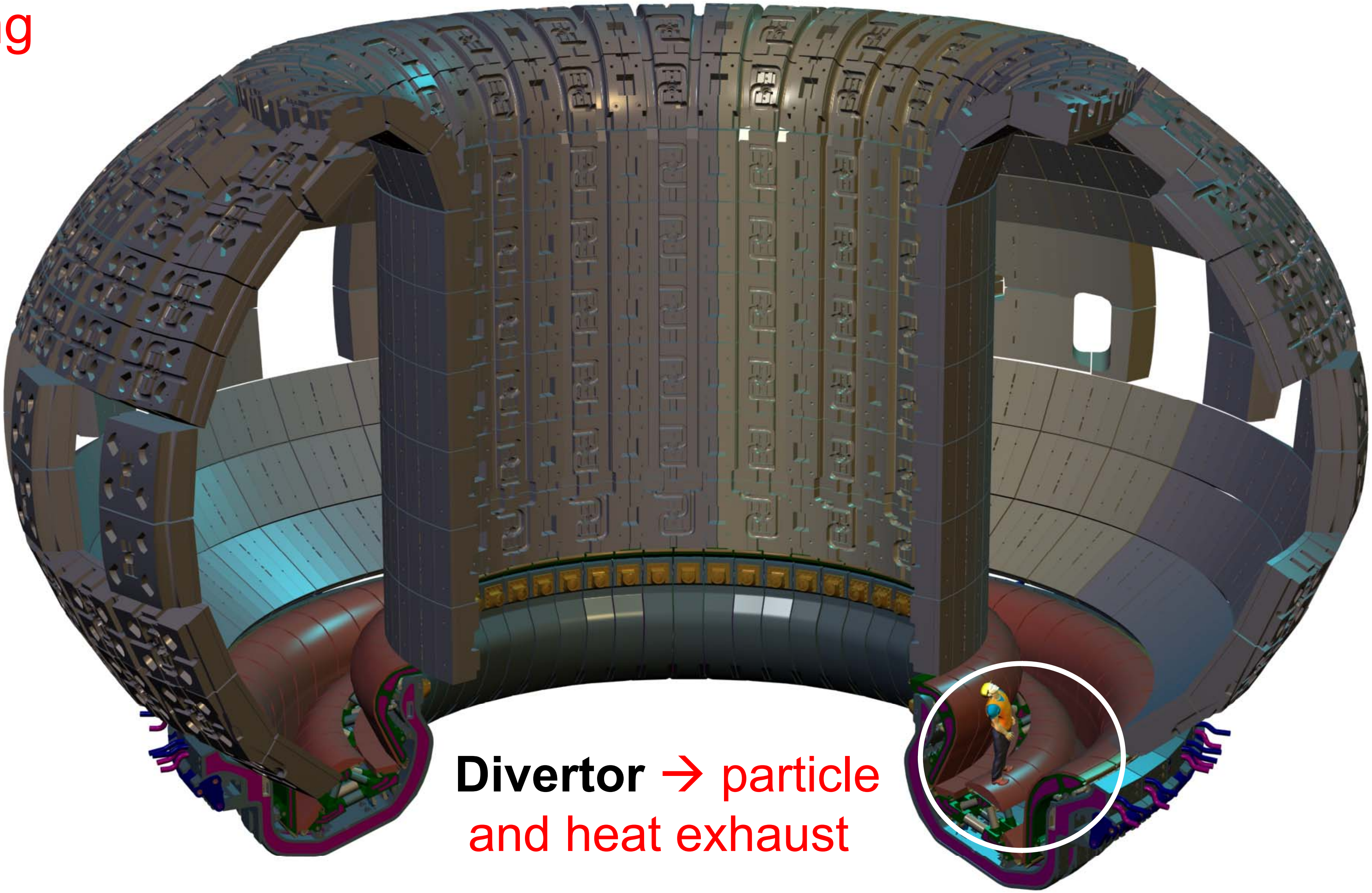
ITER burning plasma power exhaust

Power balance



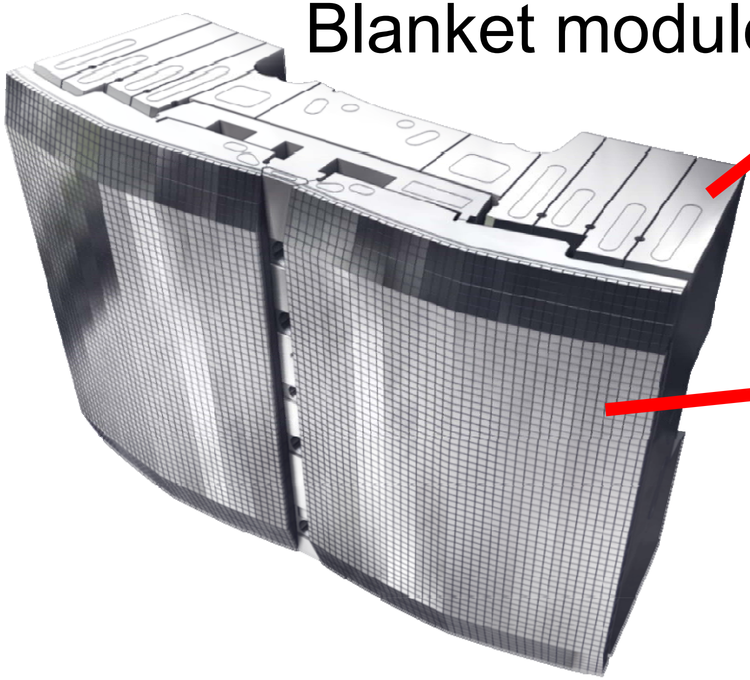
Principal plasma-facing components (PFC)

Blanket/first wall → heat exhaust, impurity management, nuclear shielding



Divertor → particle and heat exhaust

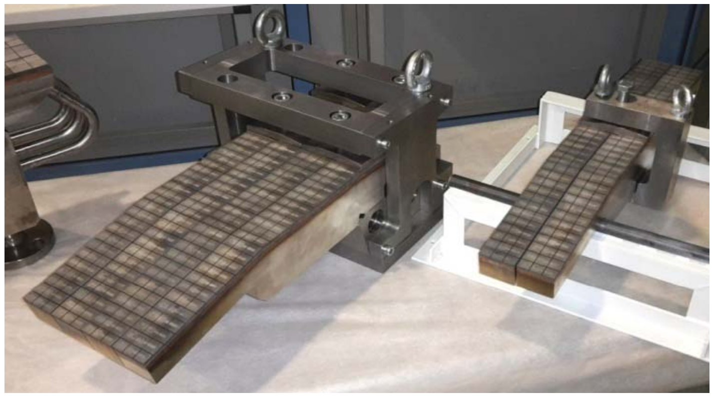
Blanket/First Wall

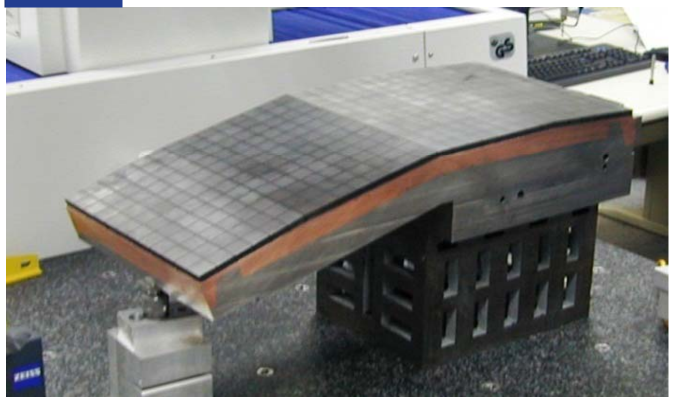


Neutron shielding:
Semi-permanent, full water-cooled massive Shield Block (SB): ~3.5±0.5 t

Plasma-facing surfaces: separable shaped First Wall Panel (FWP), armoured with Be tiles
Rated to 2 MWm^{-2} and 4.7 MWm^{-2}

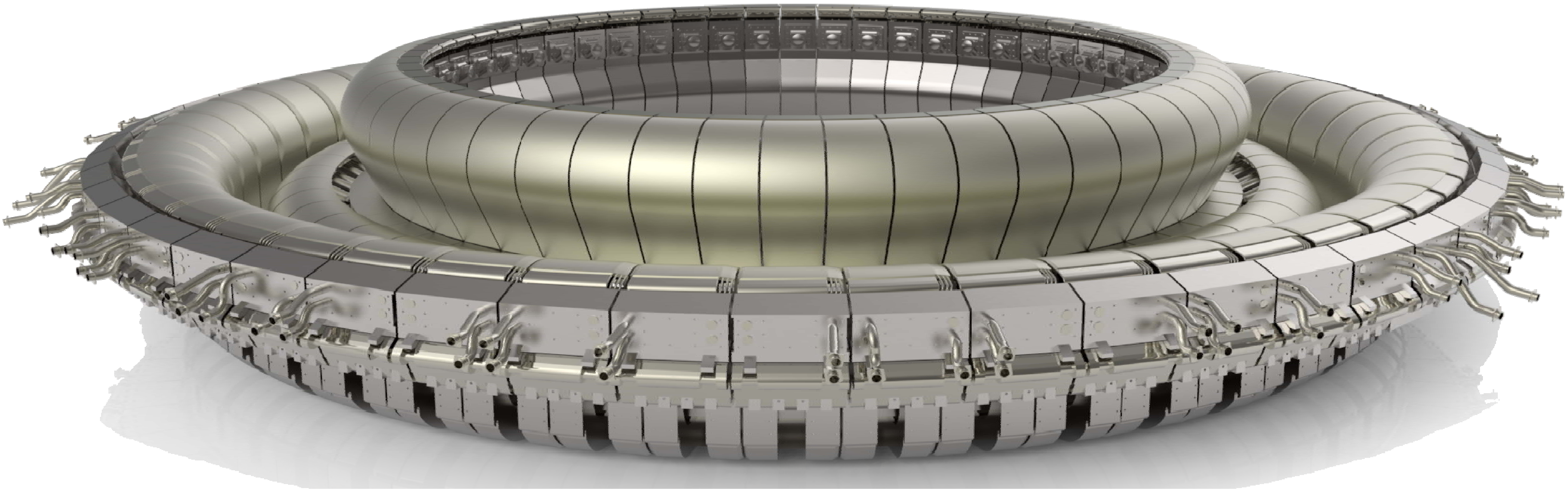
Total number of BMs: **440**
Total mass: **~1800 tonnes**





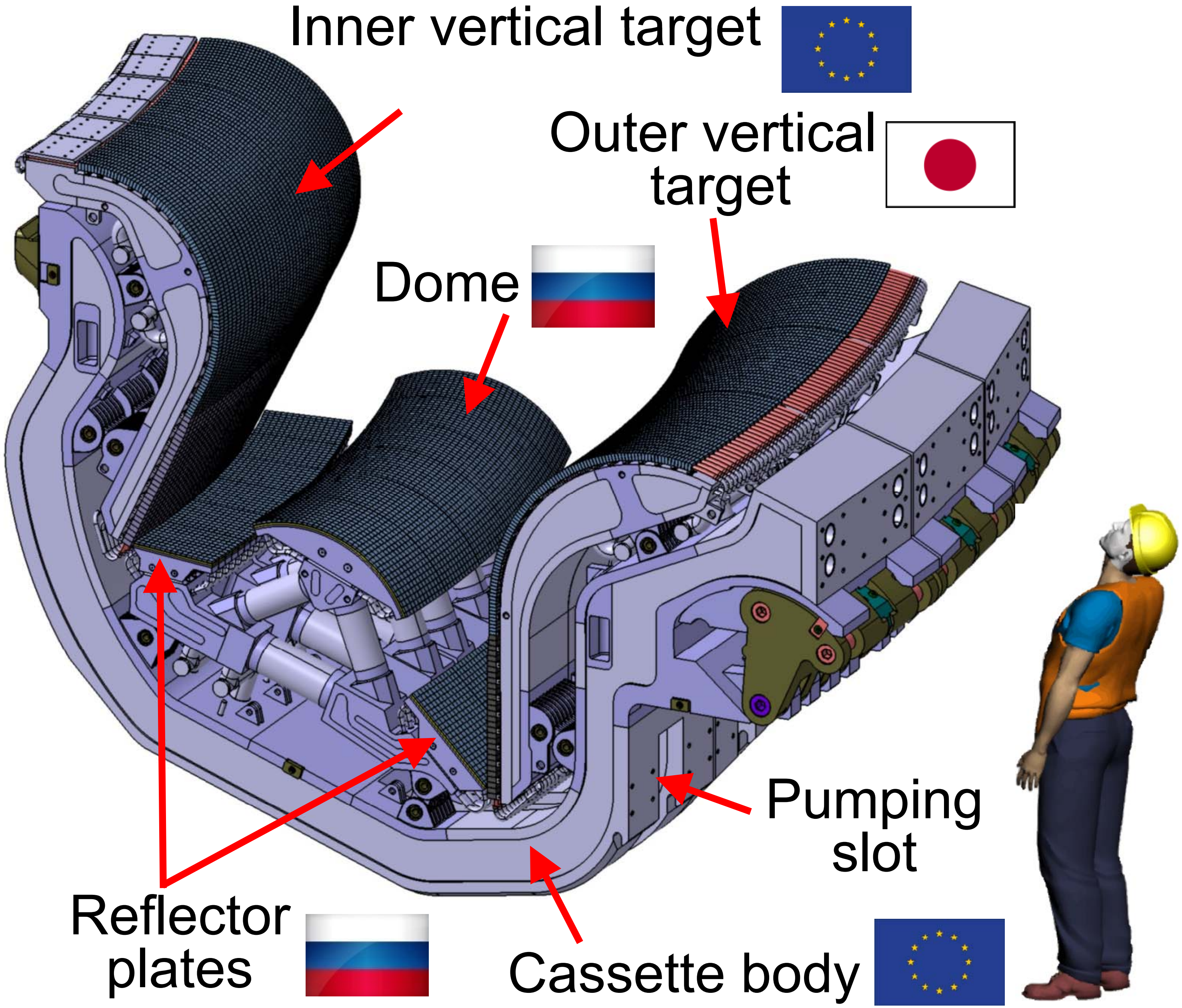
SB:
CN (50%), KO (50%)
FWP:
CN (10%), EU (50%), RF (40%)

The ITER divertor



The most sophisticated, expensive tokamak divertor ever built → will handle ~10 MWm^{-2} in steady state (about 60 MW total power).

The ITER divertor



54 divertor assemblies (~8.7 tonnes each)

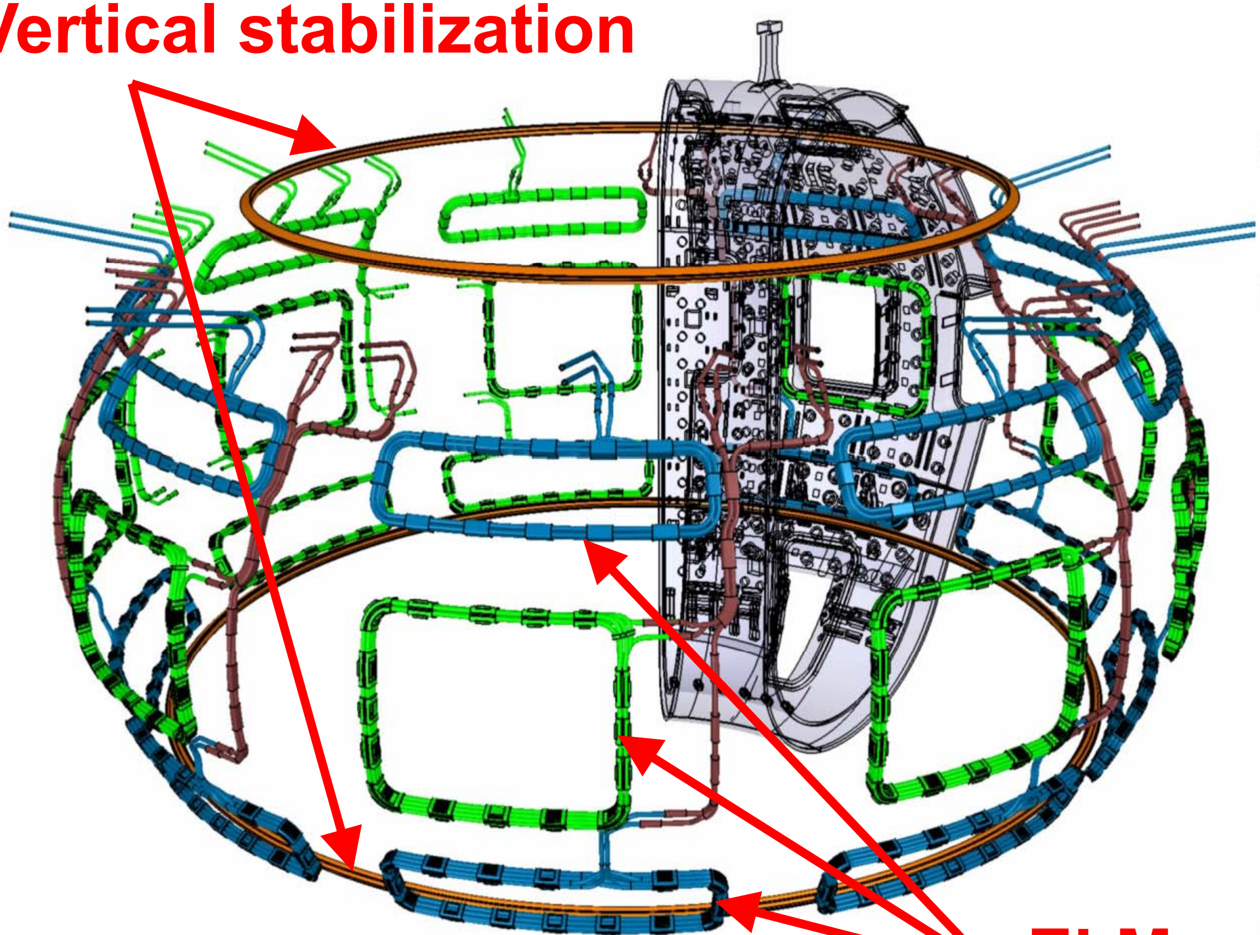
4320 actively cooled heat flux elements

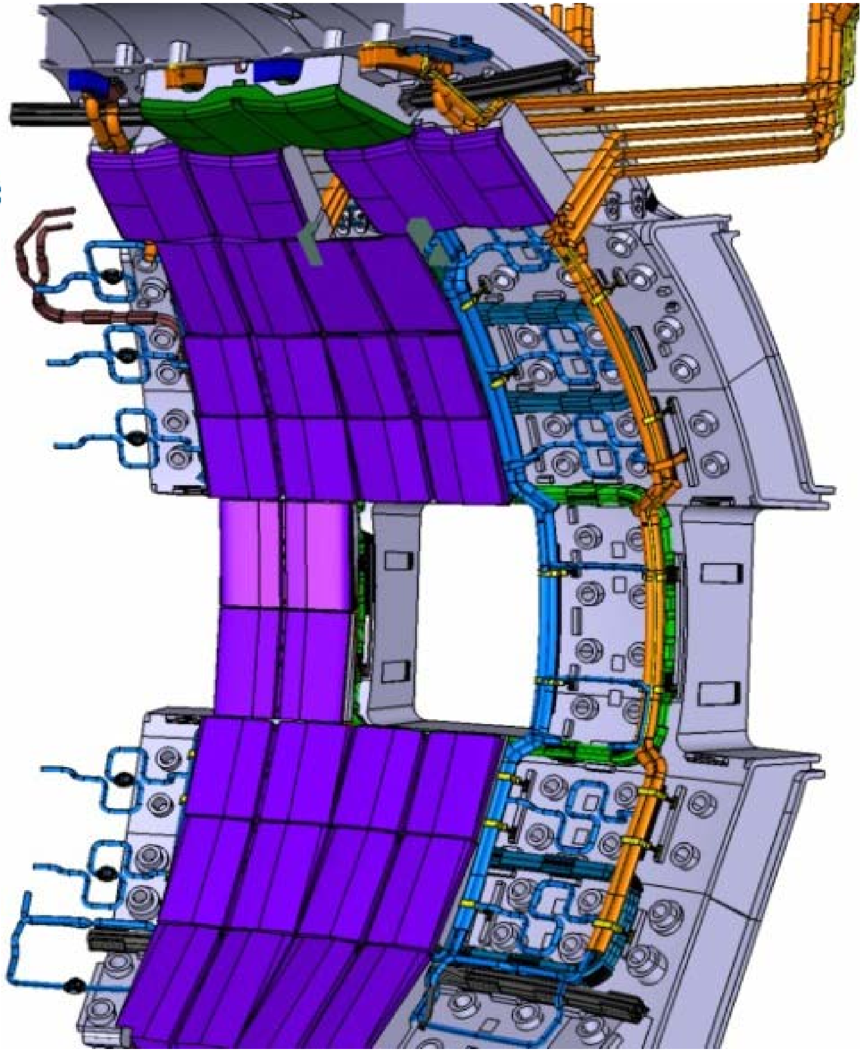
Bakeable to 350°C

All plasma-facing components will be made from tungsten

In-vessel coils (1)

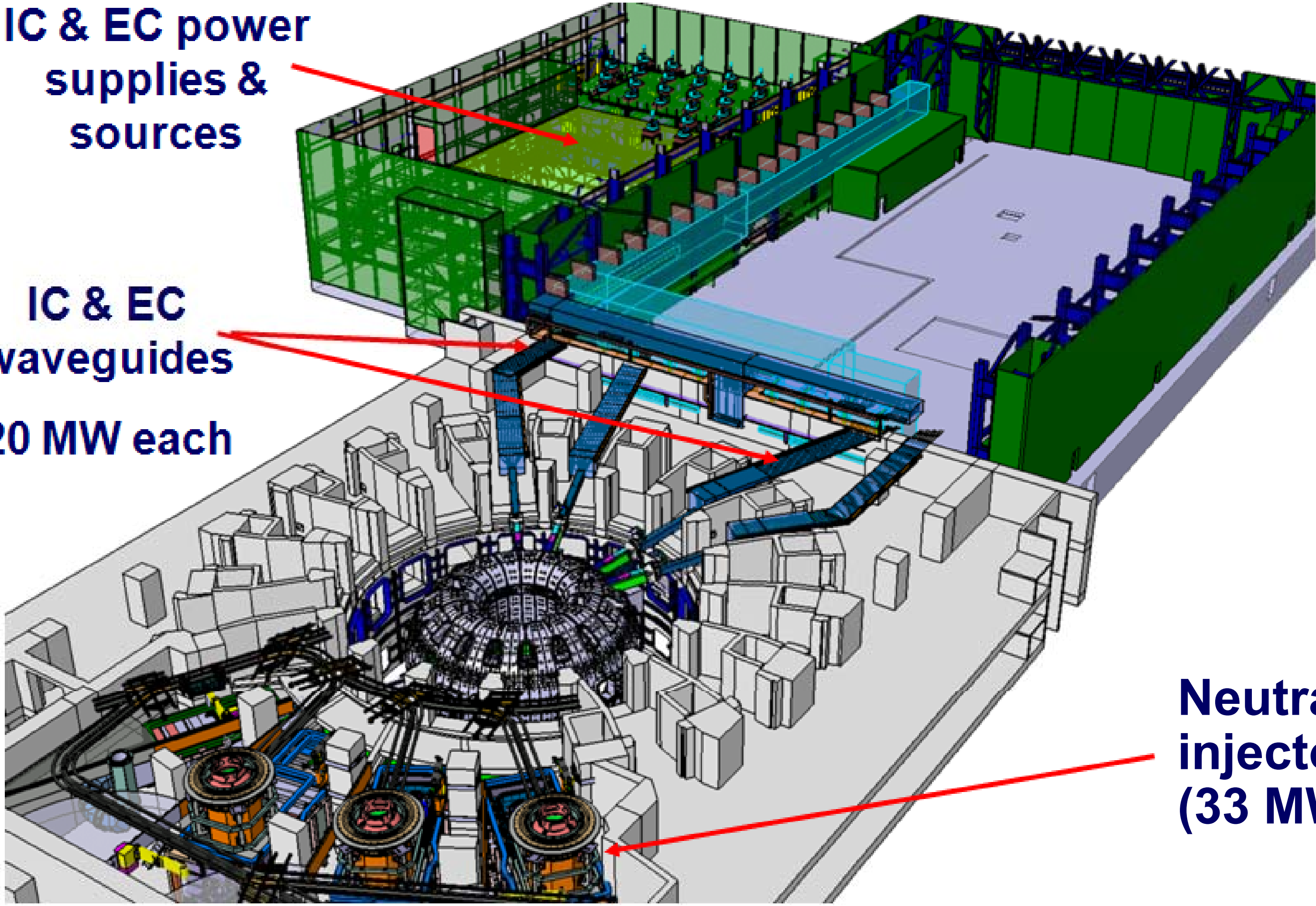
27 ELM control coils (n=4) – 3 per vacuum vessel sector (40°)





Plasma heating systems

High energy (1 MeV) neutral beams, RF heating tuned to plasma cyclotron frequencies (40-55 MHz ions, 170 GHz electrons)



RF systems follow a common design approach:

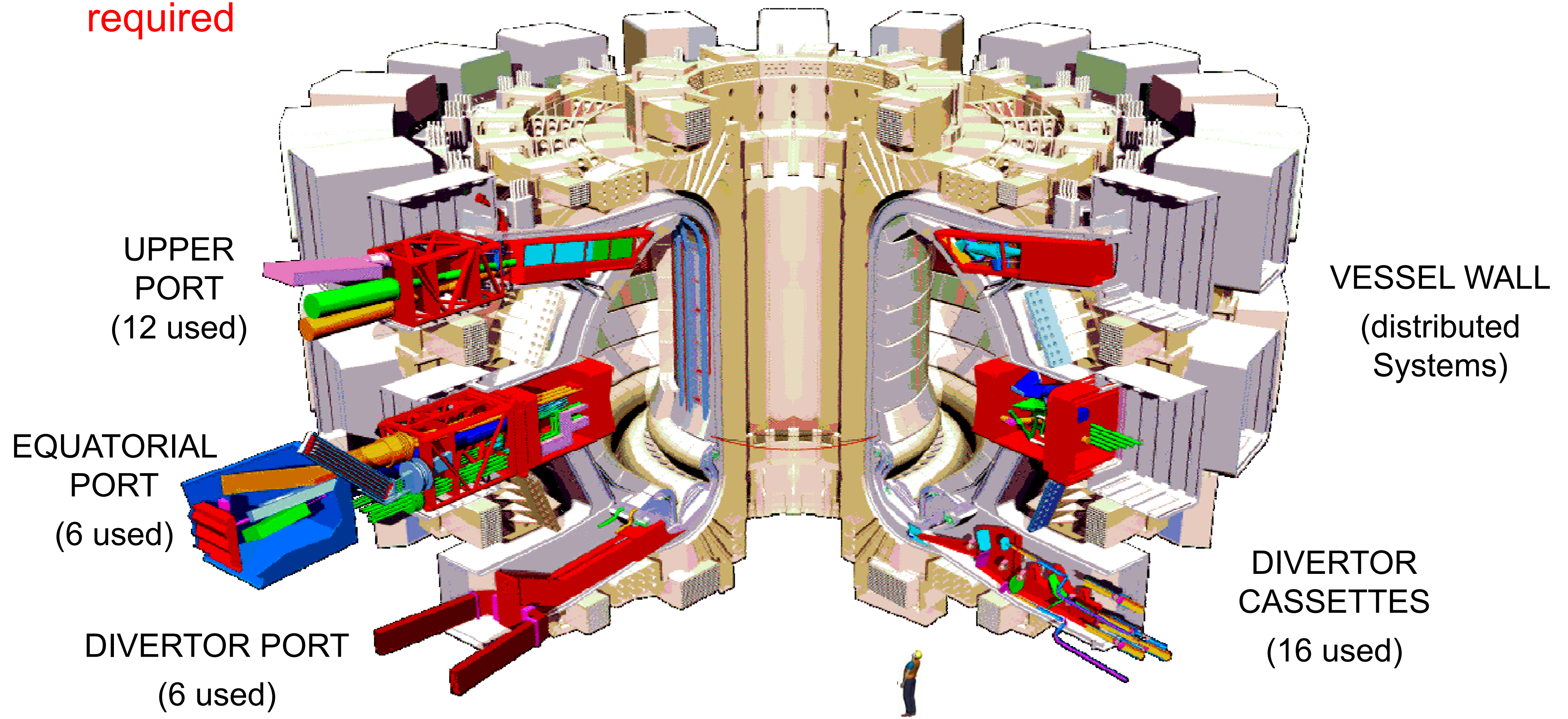
Port plug housing wave launcher

Transmission lines link port plugs to power tubes outside the torus hall

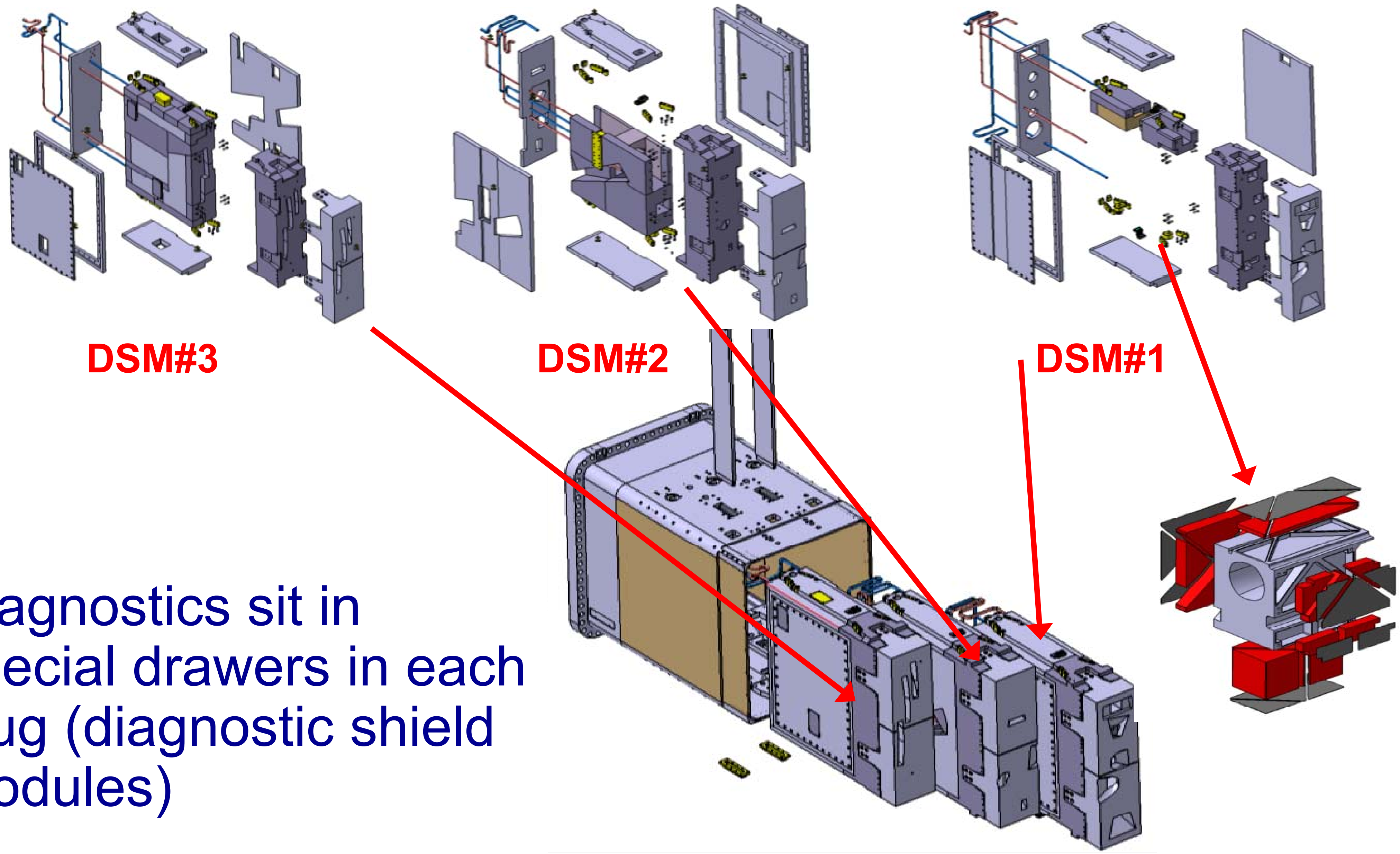
Plasma control: measurements (diagnostics)

About 40 major diagnostic systems (= very well diagnosed)

- For machine protection, control and physics studies
- Can reach peta-bytes of raw data on a “good day” → intelligent filtering will be required



Tight integration in each port plug

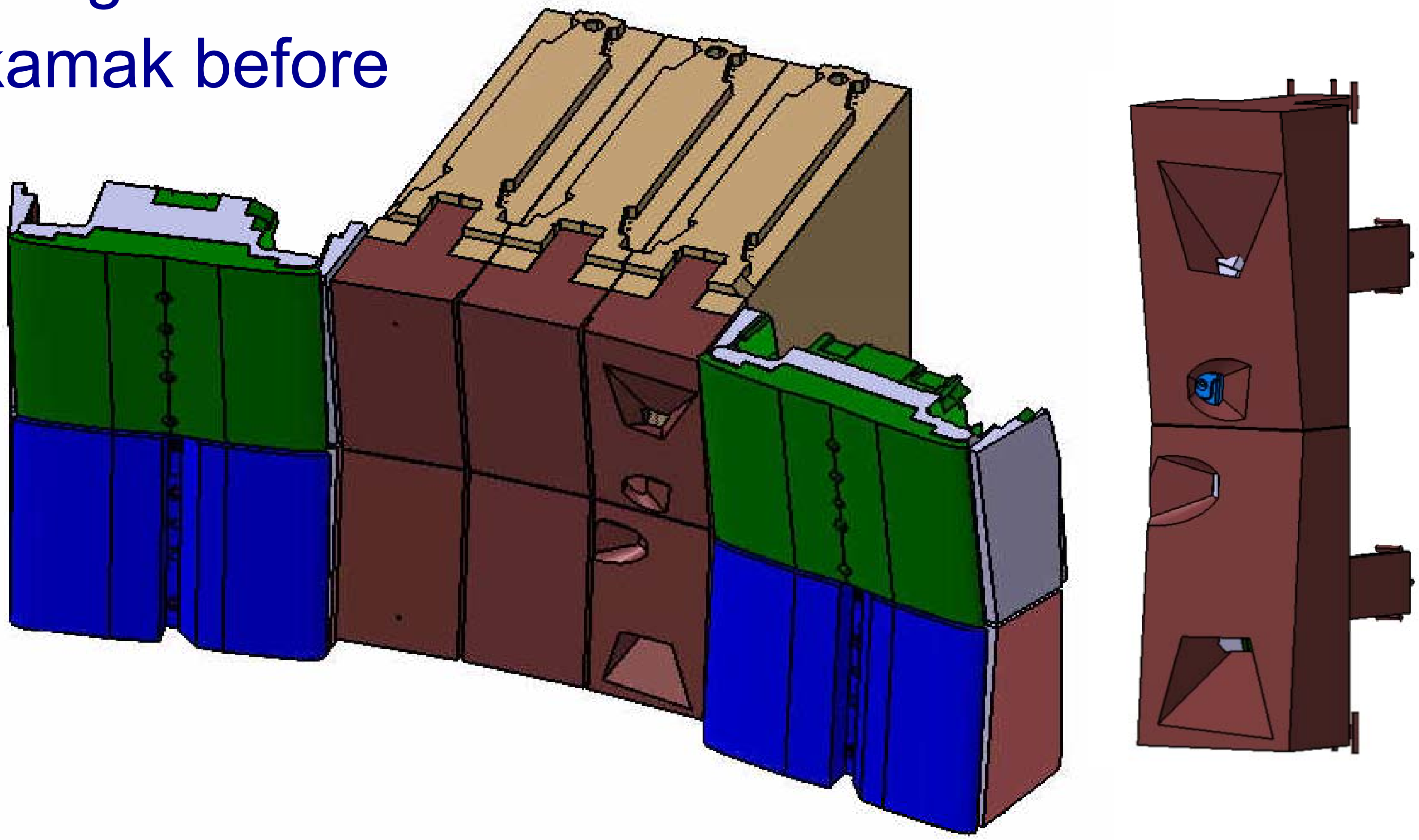


Diagnostics sit in special drawers in each plug (diagnostic shield modules)

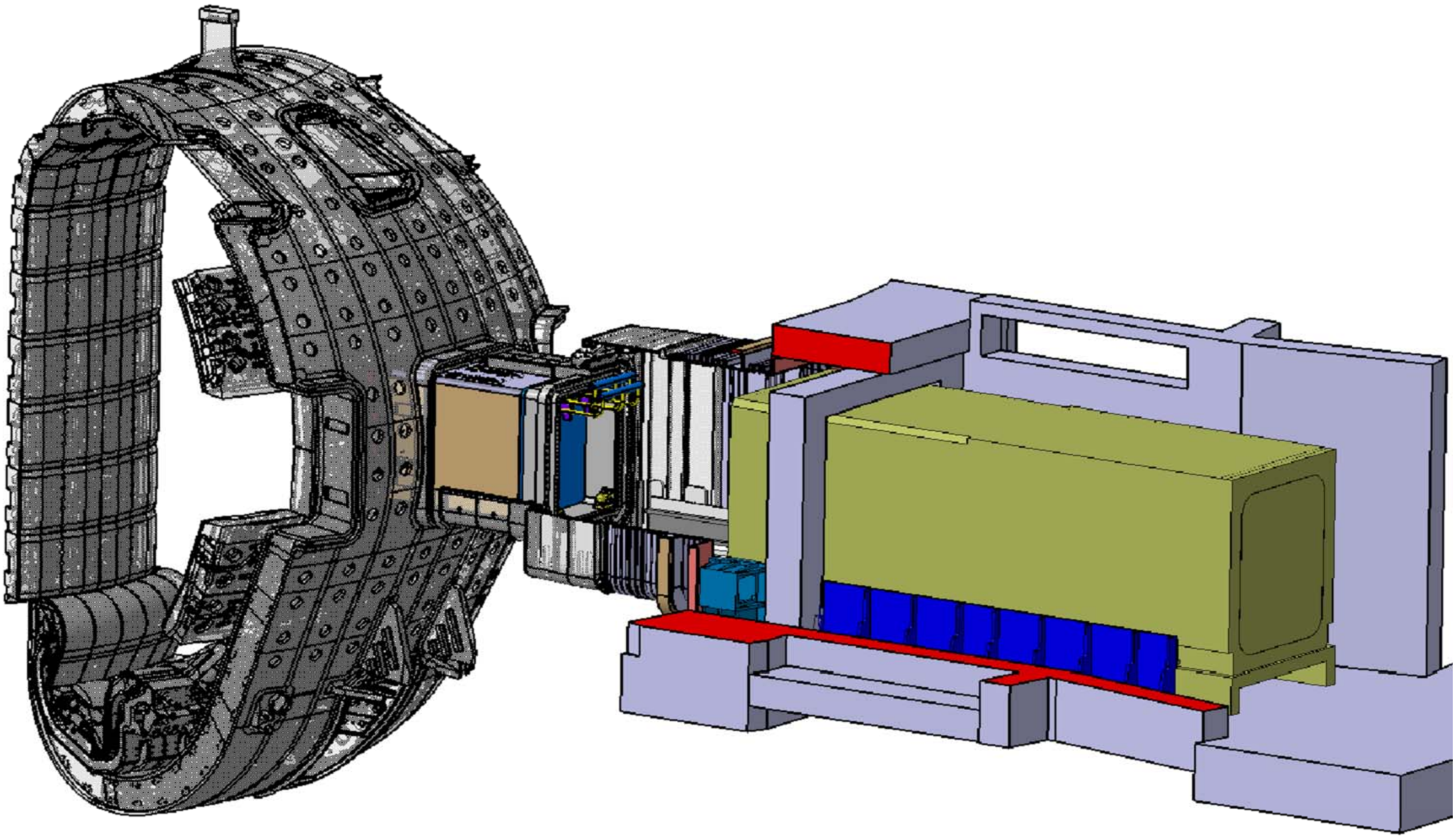
Diagnostic first wall

All diagnostics requiring views into the plasma sit behind a stainless steel `Diagnostic First Wall' → mandatory for neutron screening.

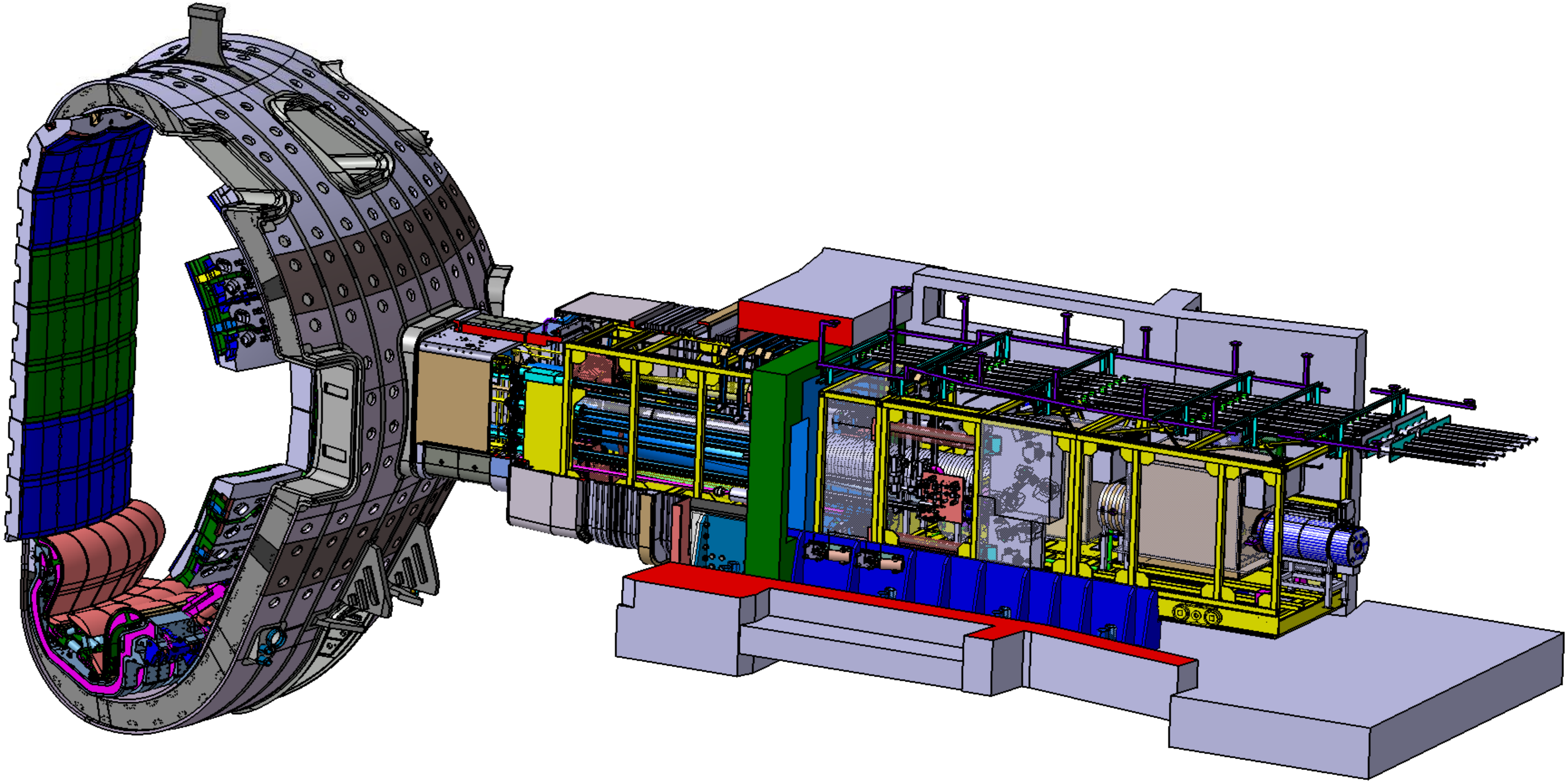
Unlike any tokamak before ITER



Assembly strategy built-in from start



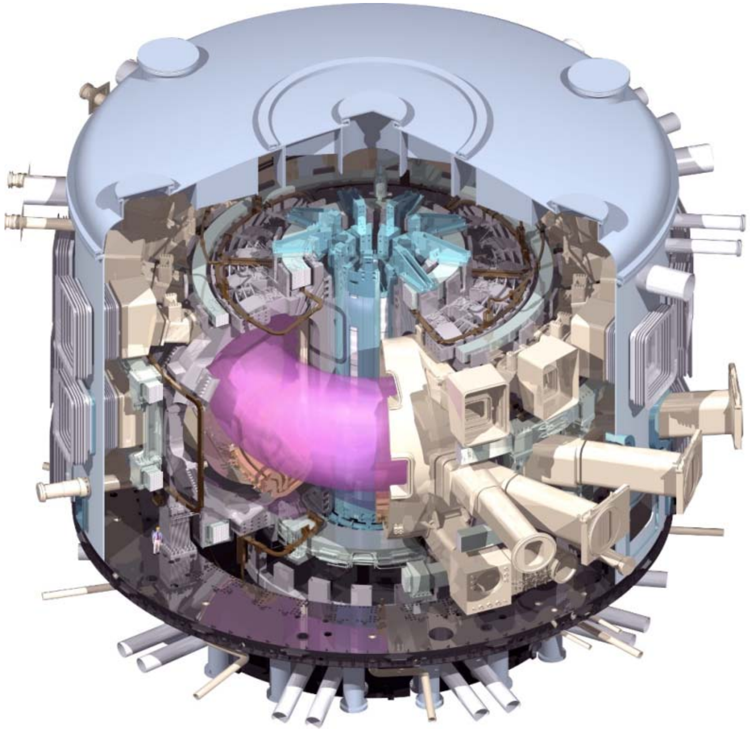
Assembly strategy built-in from start



Plasma control on ITER

- Ensure that physics objectives of any discharge are met
- Provide first level of machine protection (other levels behind)

Measurements:
~40 systems
thousands of data channels



Actuators
Magnets
Heating and current drive systems
Fuelling and pumping
~20 in total

Plasma Control System (PCS)
~20 parameters controlled simultaneously
timescales from 1 ms to several secs
(blink of an eye ~50-80 ms)
Requires state of the art control schemes

ITER Integrated Modelling Programme

Covers all aspects of physics modelling to aid planning and executing ITER Research Plan

- Extensive set of "Use Cases" requiring broad spectrum of codes

Successful development and implementation requires close collaboration with ITER Members' fusion programmes

- Advise on choice of models to address Use Cases and help validate models through verification/benchmarking activities (code-code/code-expt)

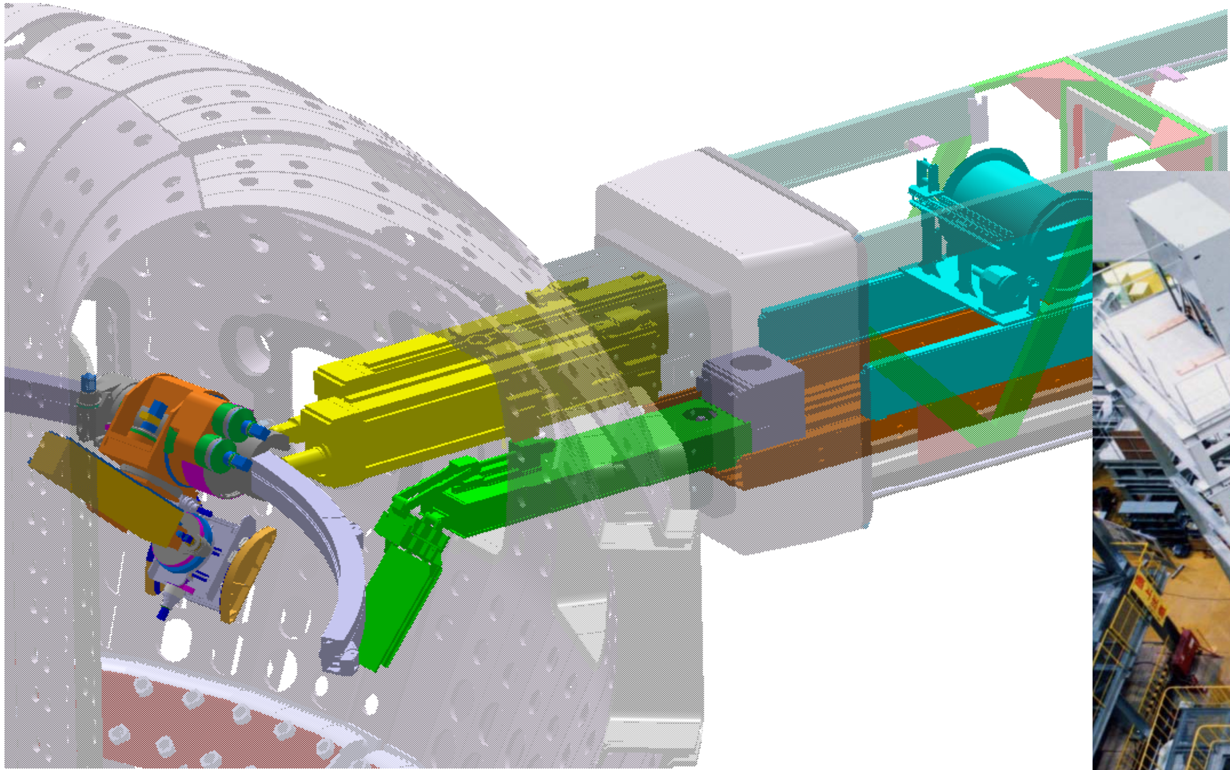
Prototype Integrated Modelling & Analysis Suite (IMAS) Framework now running on ITER's HPC cluster

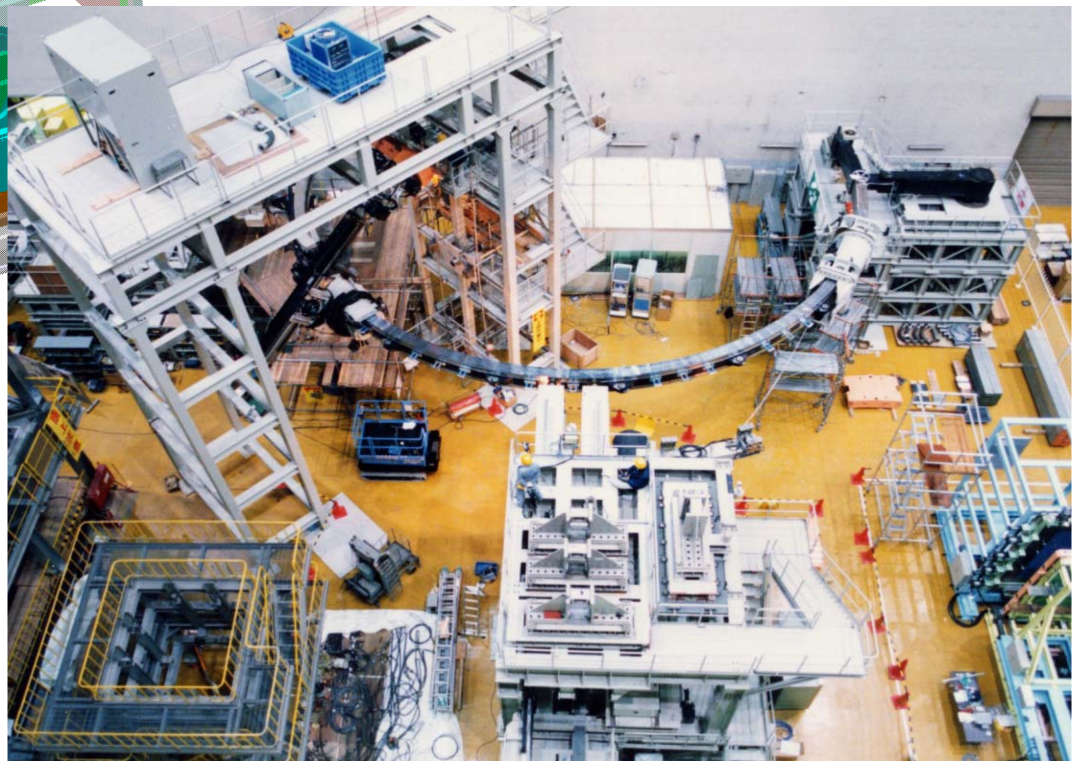
- Physics Data Model implemented to cover majority of initial workflows
- First workflows based on integrating ITER's existing physics codes
- Software management tools: Issue tracking, revision control (Git) and auto-building/regression testing for all components

Remote handling

Extremely challenging to repair and replace complex and heavy components in a nuclear environment

- Dedicated, state-of-the-art systems for both Blanket, Divertor, Port Plug removal and other in-vessel functions (e.g. inspection, dust aspiration)

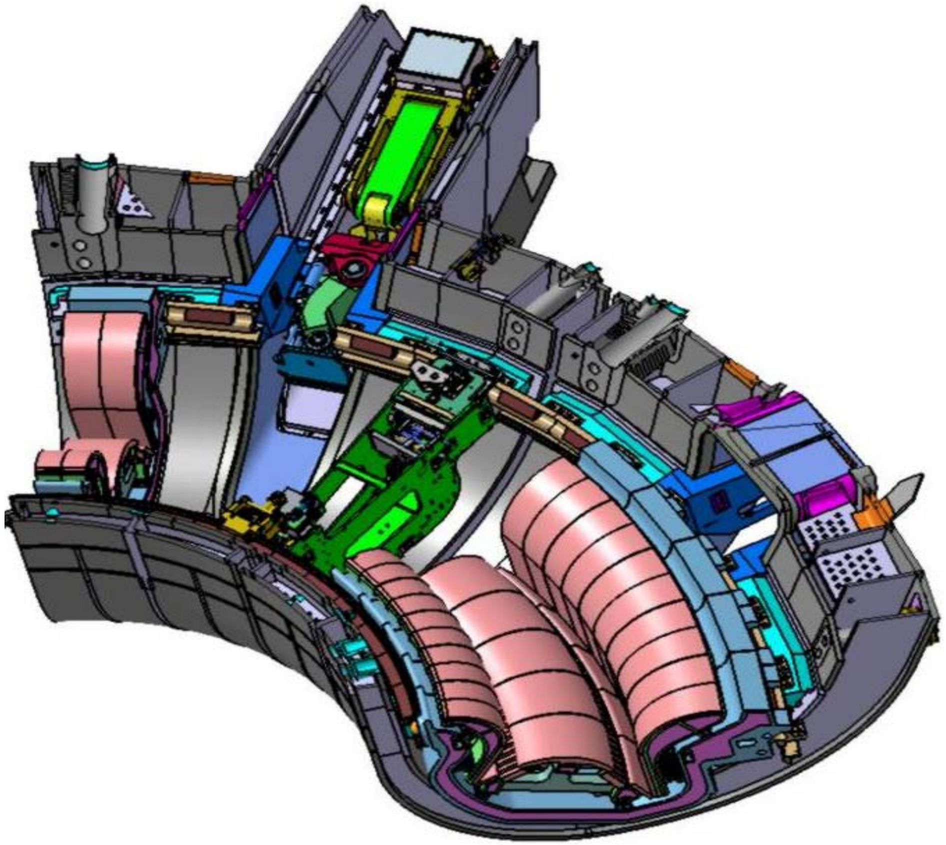


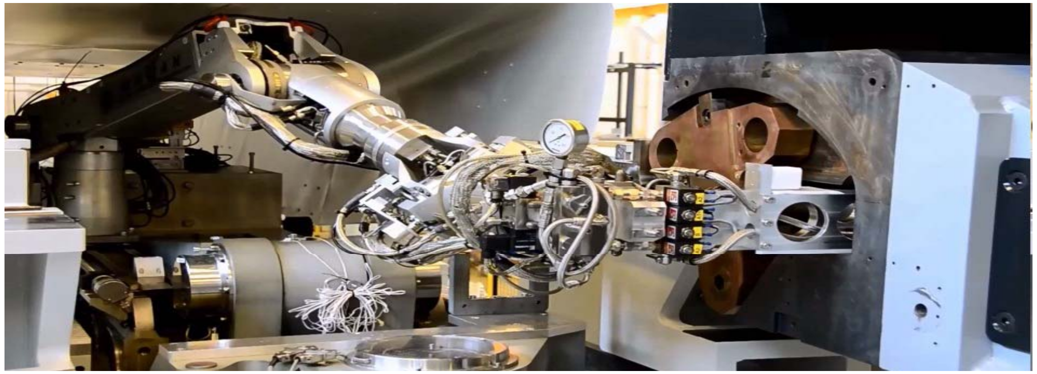


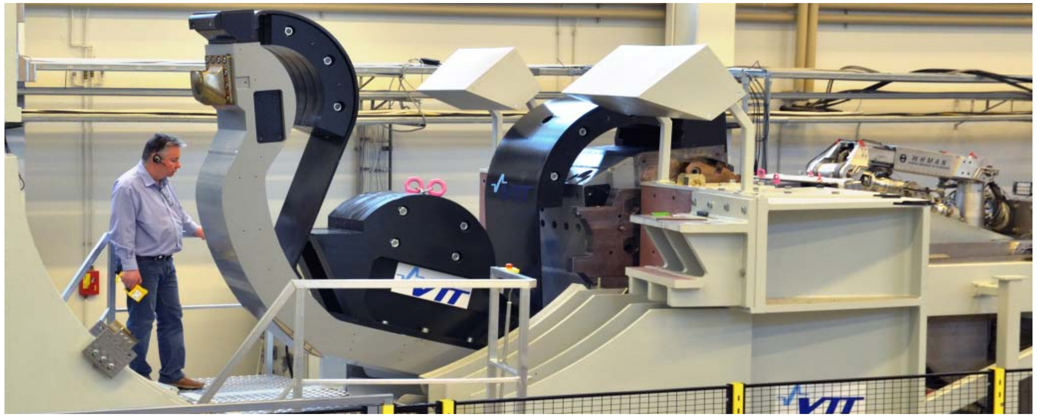
Remote handling

Extremely challenging to repair and replace complex and heavy components in a nuclear environment

- Dedicated, state-of-the-art systems for both Blanket, Divertor, Port Plug removal and other in-vessel functions (e.g. inspection, dust aspiration)







Nuclear operation: tritium reprocessing – the T-Plant

Of the ~ max 100 g of tritium fuel per Q=10 pulse, only ~0.3% will be burned by fusion reactions → T reprocessing is required

- using existing technologies but on a much larger scale (~factor 10)

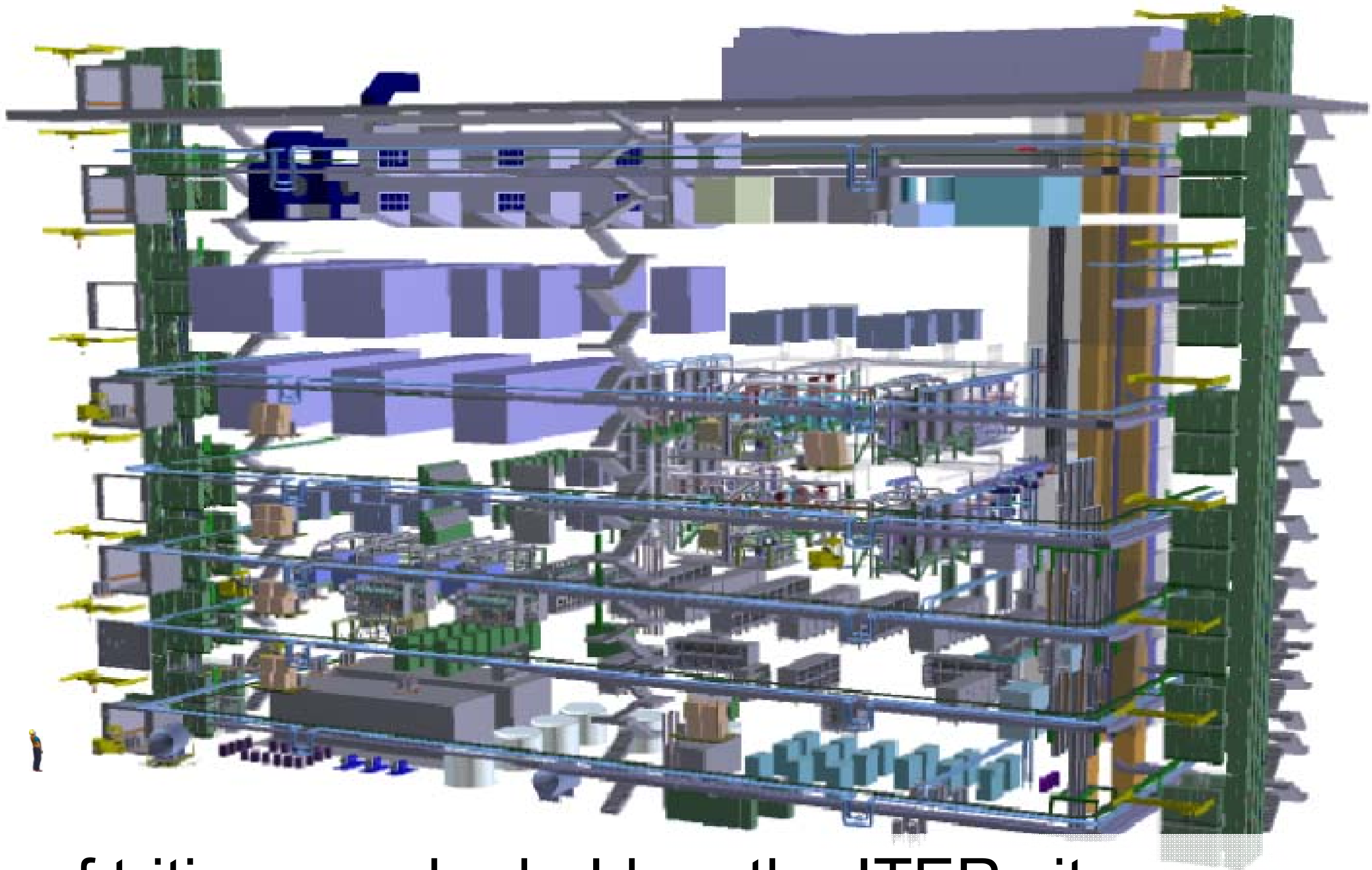
7 floors

(2 below ground level)

L = 80 m

W = 25 m

H = 35 m



A maximum of 4 kg of tritium can be held on the ITER site

A word on tritium supply

Half-life of T: 12.32 years

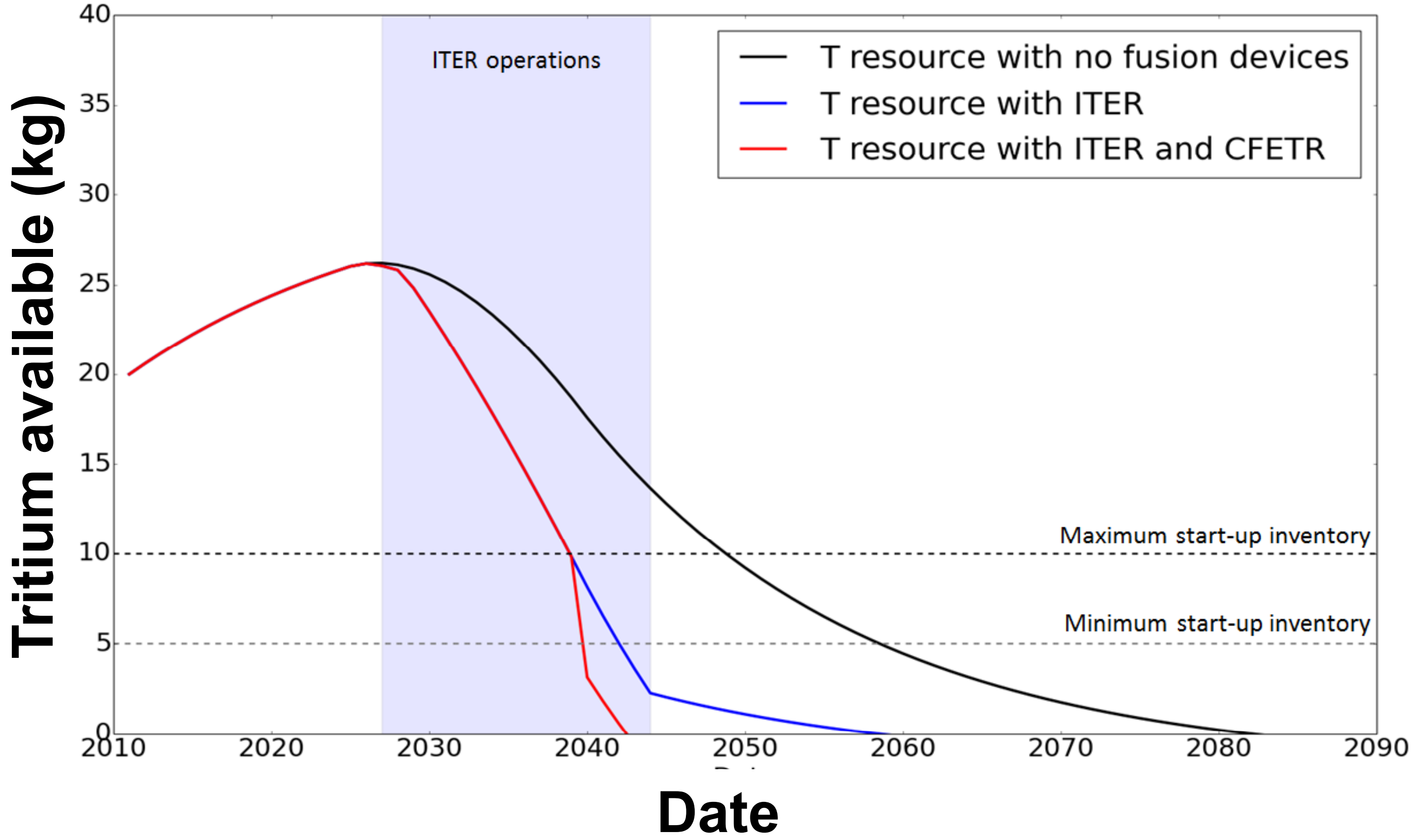
Decays ~5.5% / year

Vast majority of production is waste product of CANDU fission reactors

Production is 27 kg T from over 40 years exploitation

A 2GW (500 MWe) DEMO fusion will burn ~110 kg T per full power year

Courtesy Matti Coleman, PPPT



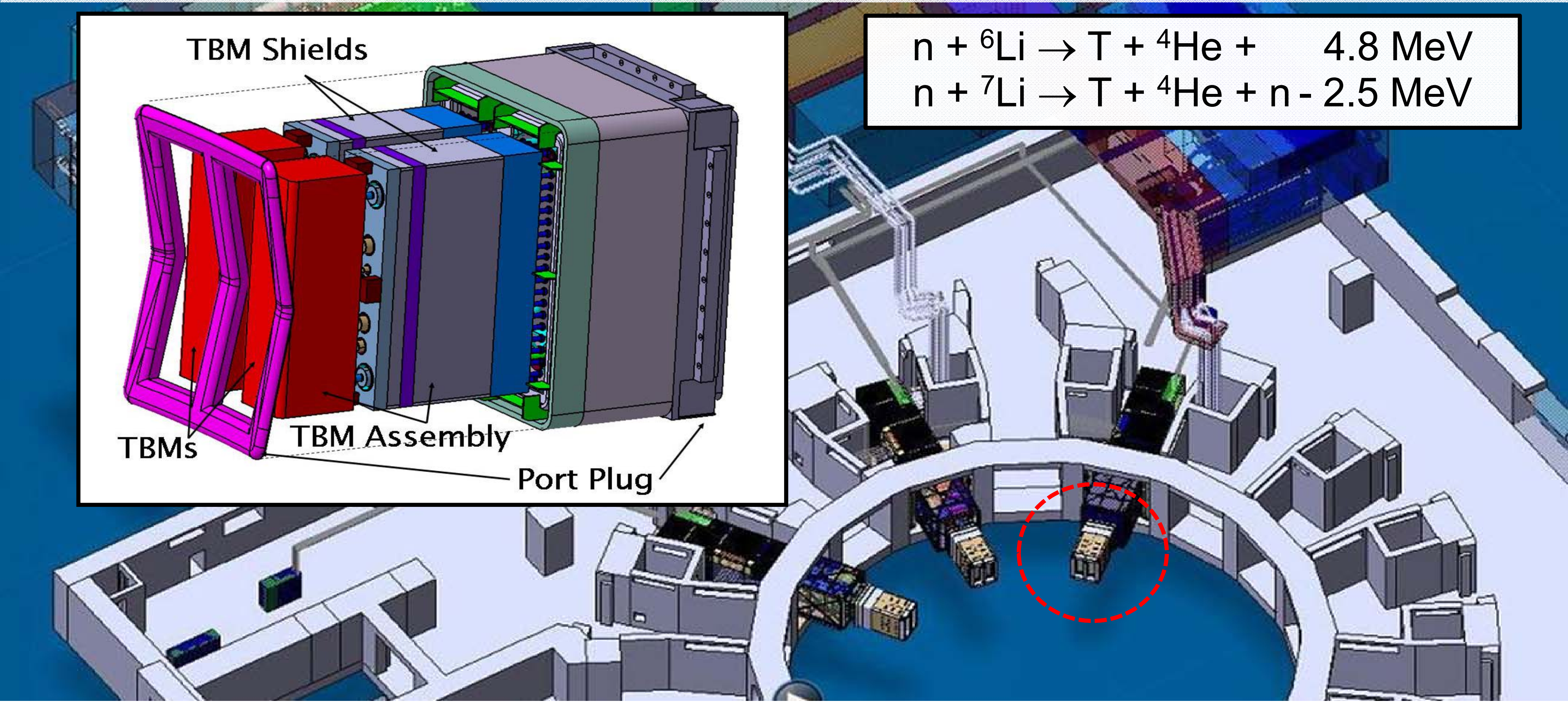
If ITER succeeds (if it achieves the projected P_{FUS} and/or neutron fluence), it will require ~17 kg T in lifetime.

→ Realistically, DEMOs after ITER have to be tritium breeders

Nuclear operation: tritium breeding modules (TBMs)

Tritium fuel cycle is thus a major challenge for all DT fusion devices → ITER will test concepts

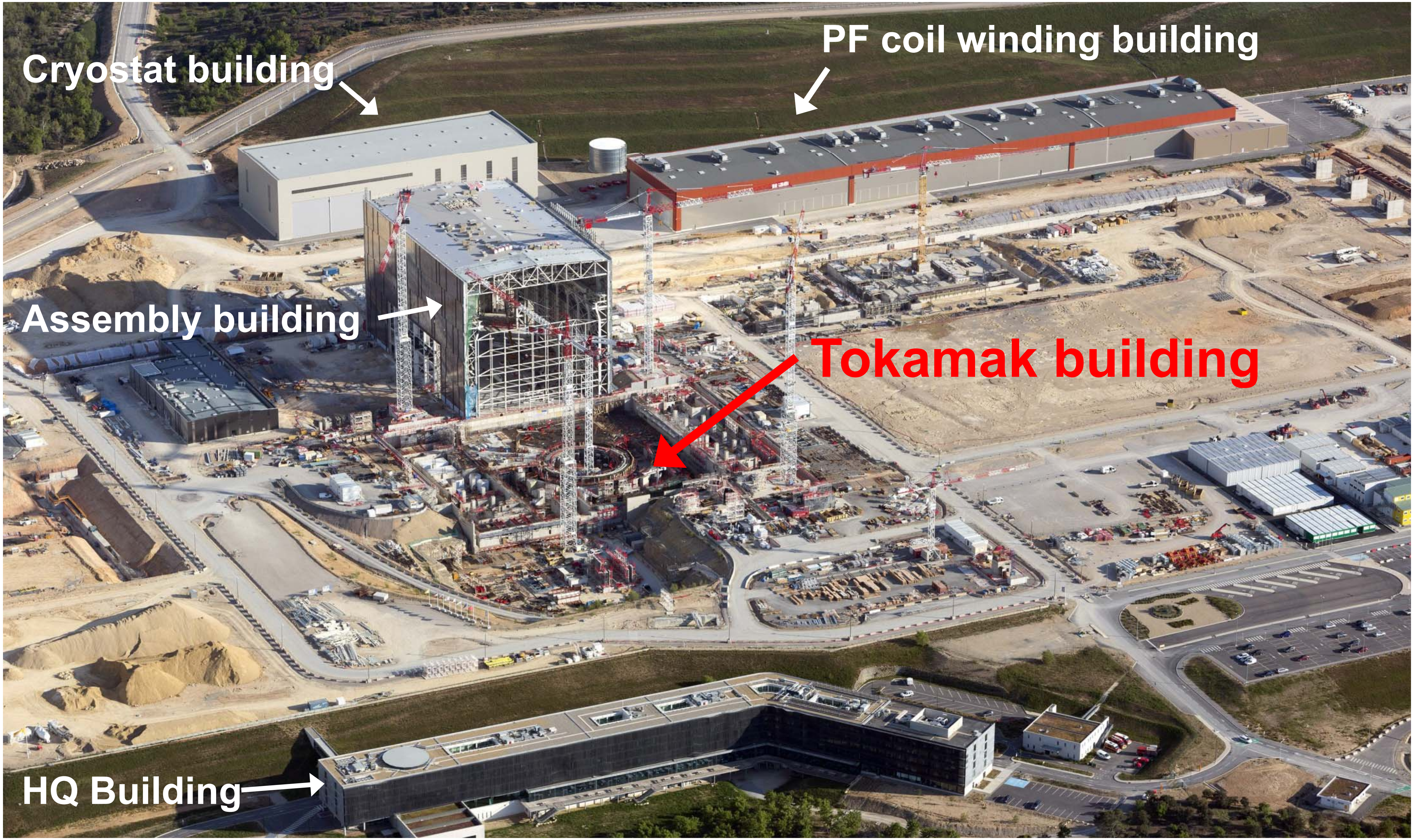
- 6 modules with different designs, all ITER parties involved



$$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8\ MeV$$
$$n + {}^{7}Li \rightarrow T + {}^{4}He + n - 2.5\ MeV$$

Construction and the ITER site

The ITER site: aerial view April 2016



PF coil winding building

Poloidal field coil winding building: ~257 m long, 45 m wide, 18 m high

PF coil winding building

PF coil winding building

This large beam spreader handles the heavy loads during the coil winding and assembly process

iter china eu india japan korea russia usa

PF winding tools arriving

23 May 2016

Winding tool for PF coils #2 and #5 now in place

Cryostat base support system

11 July 2016

Circular steel frame to support the cryostat base sections during welding operations. Diameter 34 m (cryostat building width 44 m)

Cryostat base welding underway

12 Sept. 2016

The 6 Tier 1 segments (50 tonnes each) of the cryostat base are positioned on the assembly frame and aligned (optical metrology) such that each is separated by a 4 mm gap to be filled by welding.

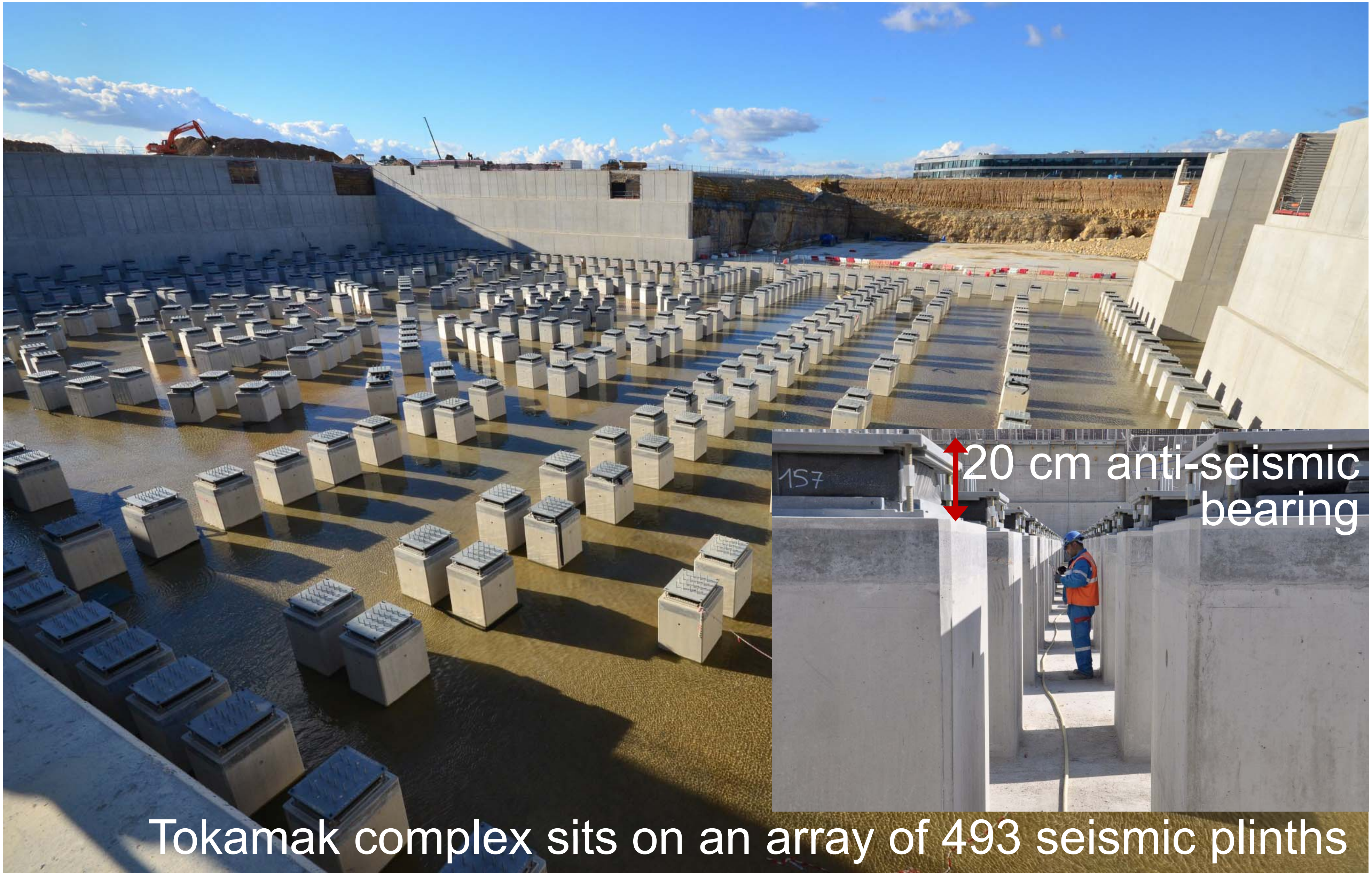
Tokamak complex construction

The three buildings of the Tokamak Complex share a single foundation: a monolithic structure which avoids relative displacements

At 5:00 a.m. on Tuesday, 9 August, foundation pouring begins to create the basemat of the Seismic Pit

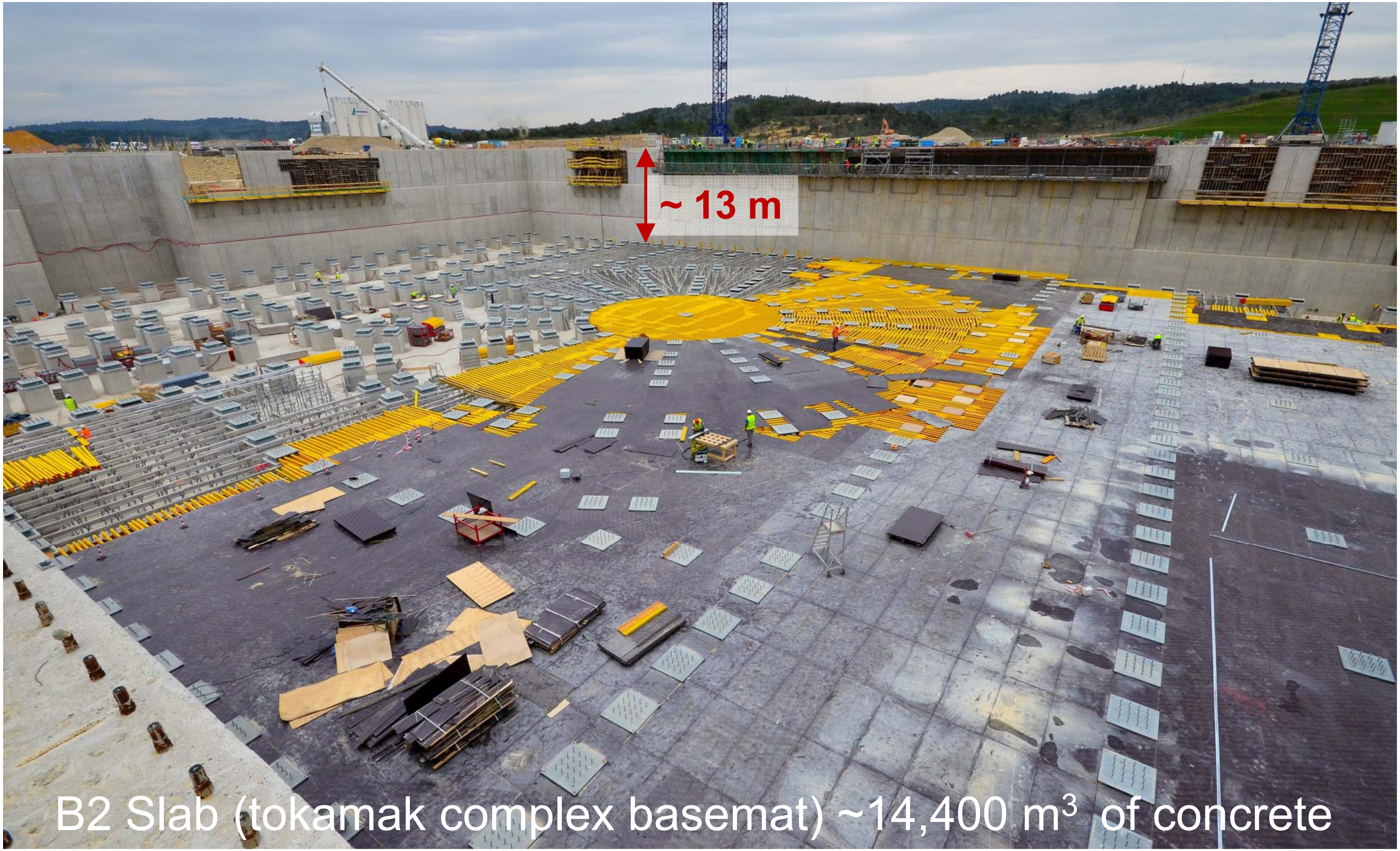
Tokamak complex construction

January 2013

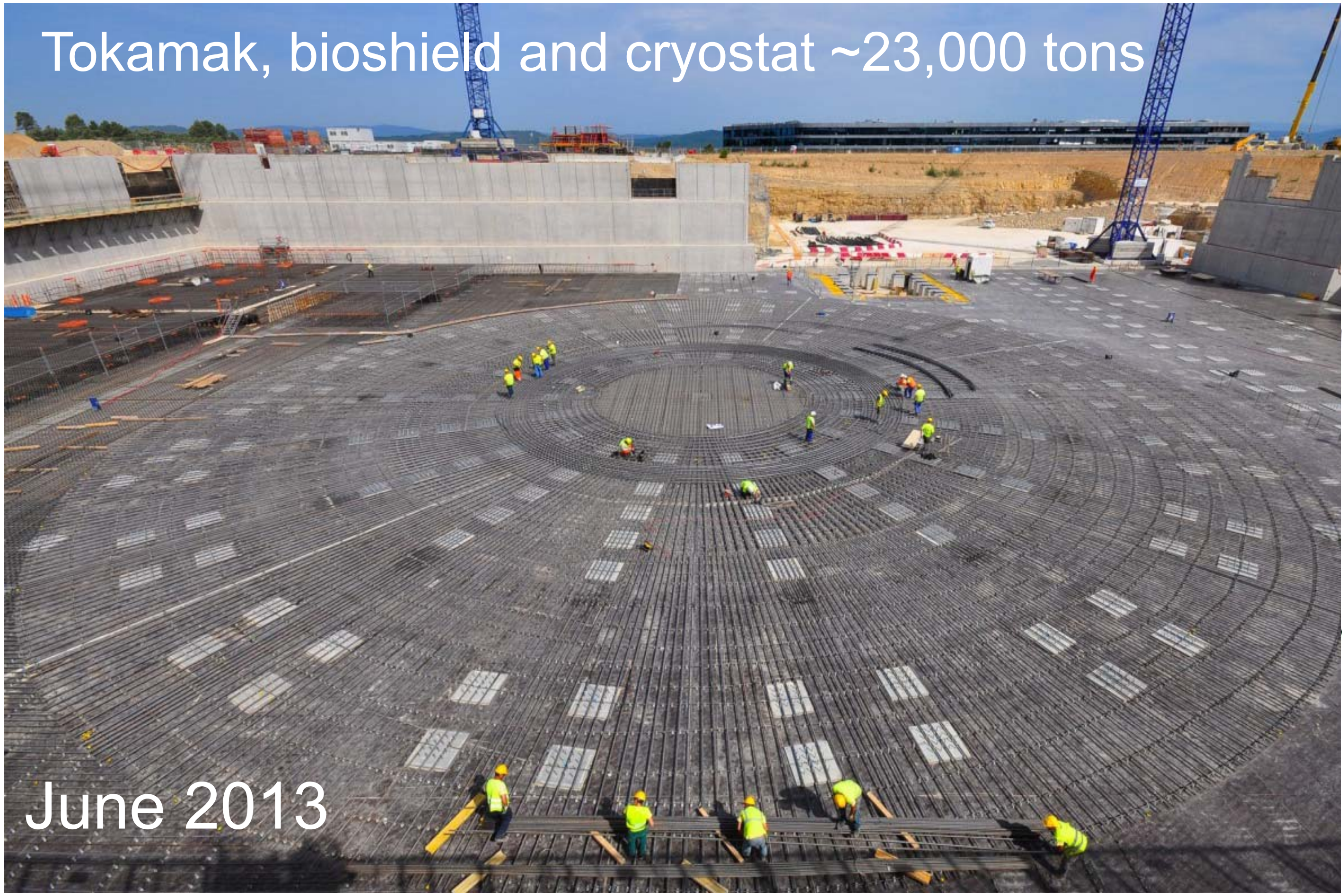


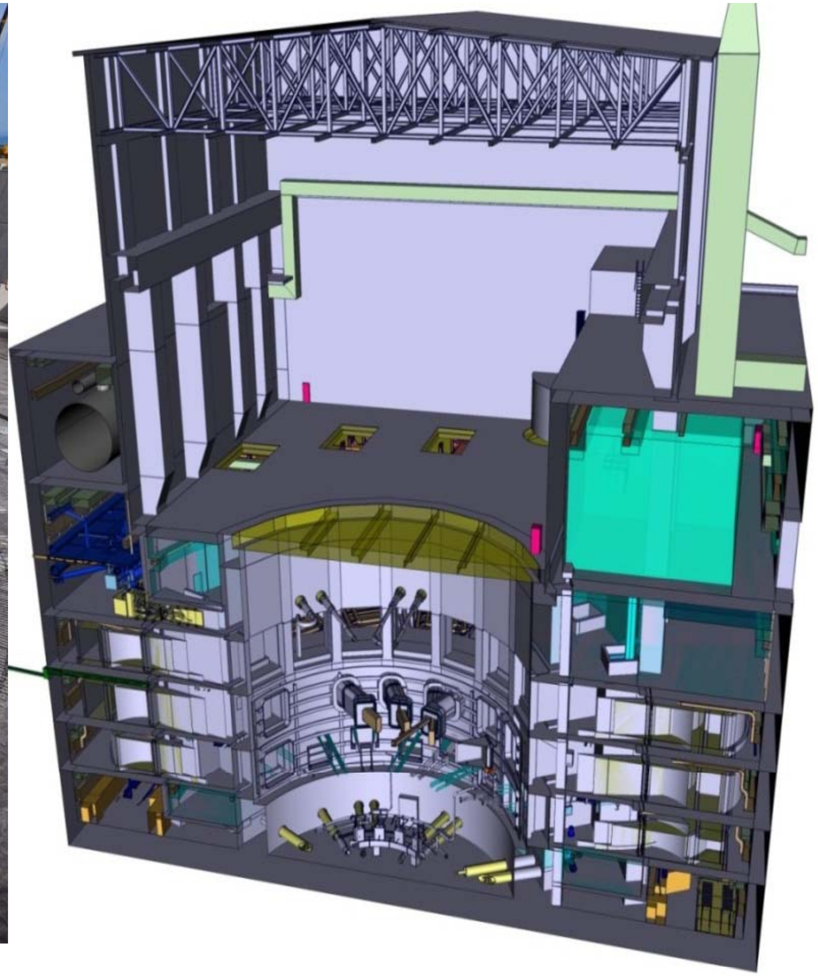
Propping and formwork for B2 slab

April 2013



Rebar for pouring of B2 slab





B2 slab supports the 360,000-tonne Tokamak Complex.

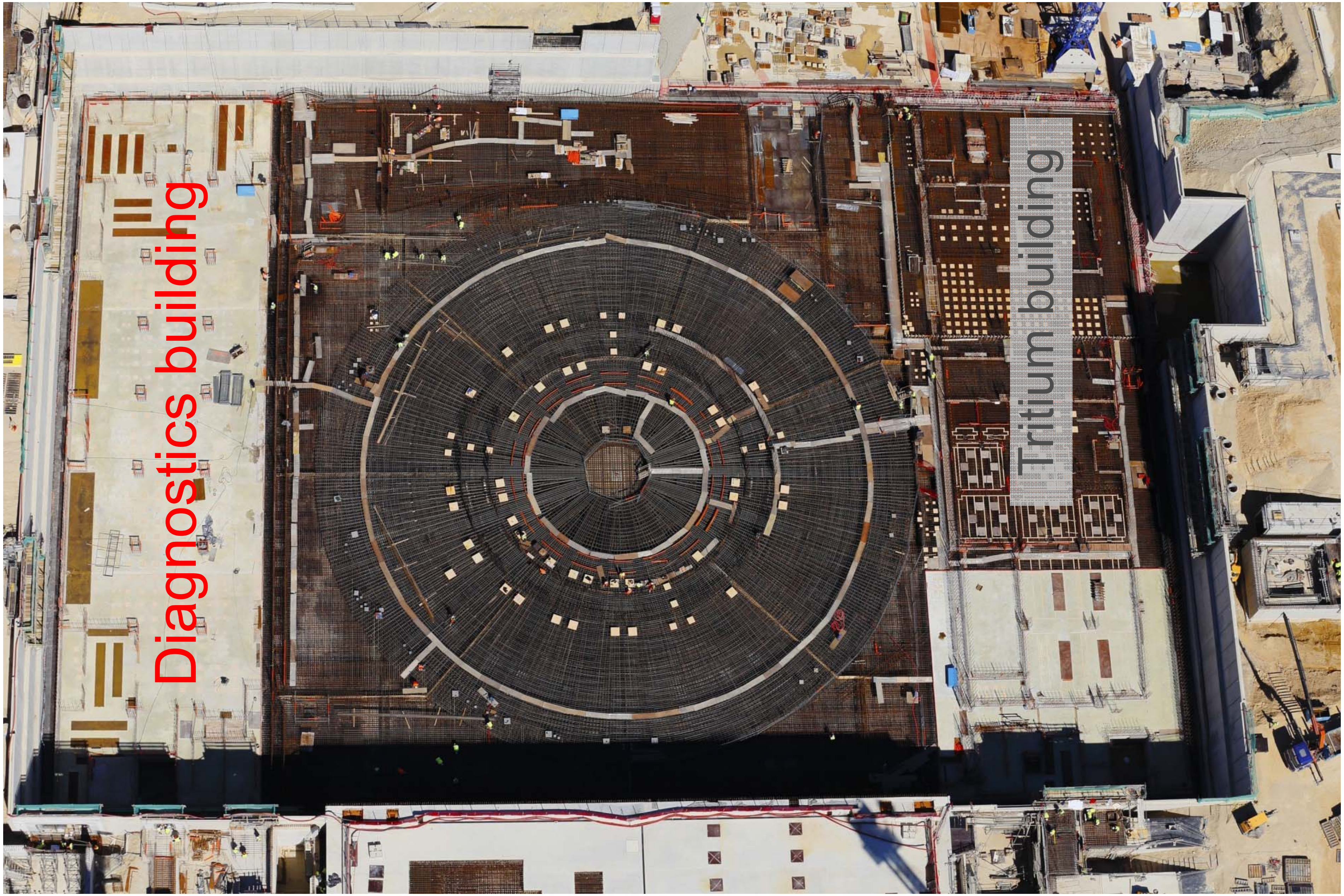
Rebar for pouring of B2 slab

August 2013

Pouring Concrete Begins

December 2013

Aerial view of concrete pouring process



29 April 2014

Embedded plates positioned before pouring

First central segment of B2 slab poured

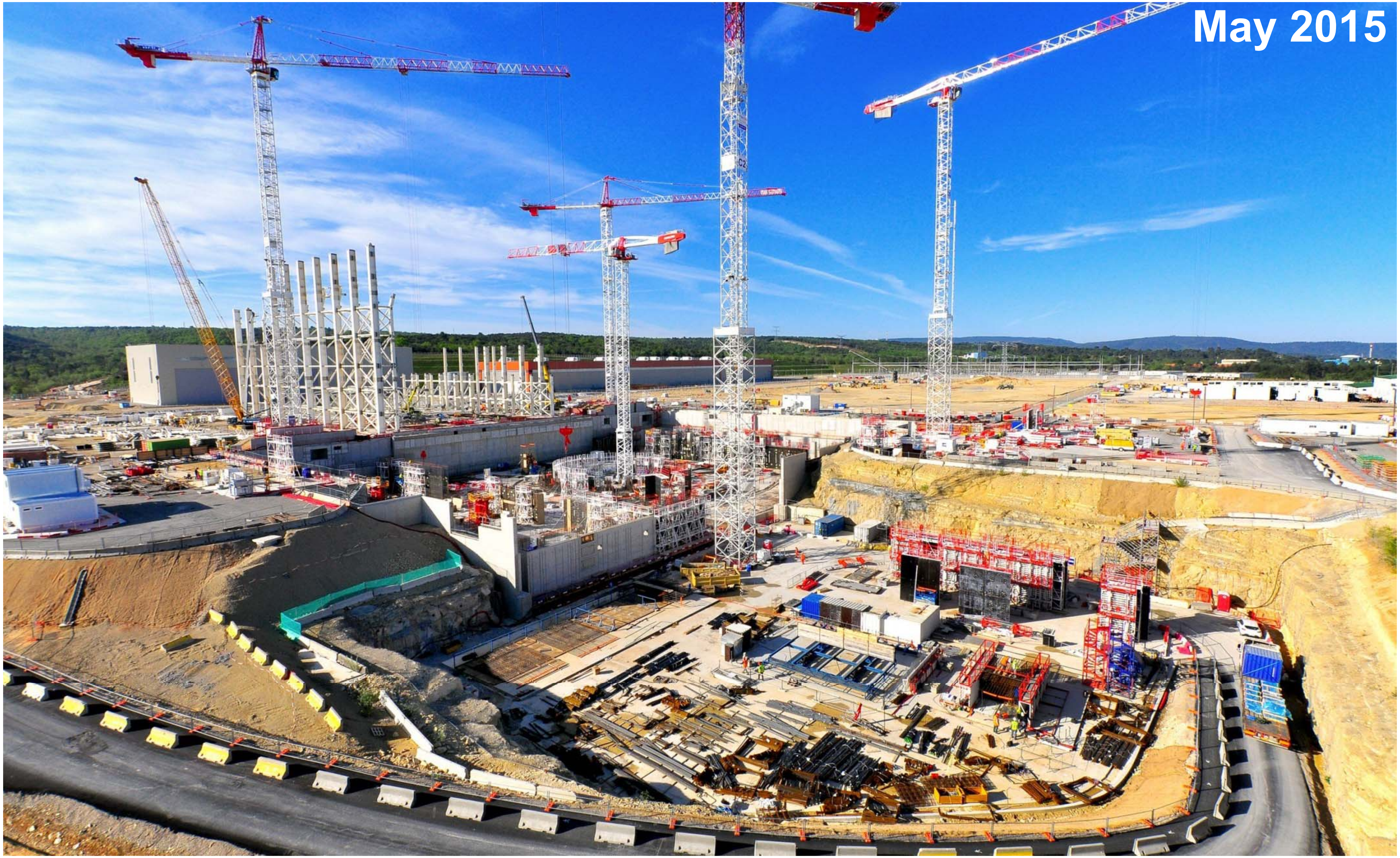
10 July 2014

15th and final central segment poured

27 August 2014

Completed B2 slab

Hot cell complex



Assembly building: raising the roof

Sept. 11 2015

Assembly hall view from rear

Giant crawler crane temporarily installed on site in June to lift the elements of the Assembly Hall travelling cranes into place.

June 14 2016

Assembly Hall cranes installed

June 27 2016

Two main cranes in the Assembly Hall: travelling cranes carry together loads of up to 1,500 tons from the Assembly Hall to the Tokamak installation area.

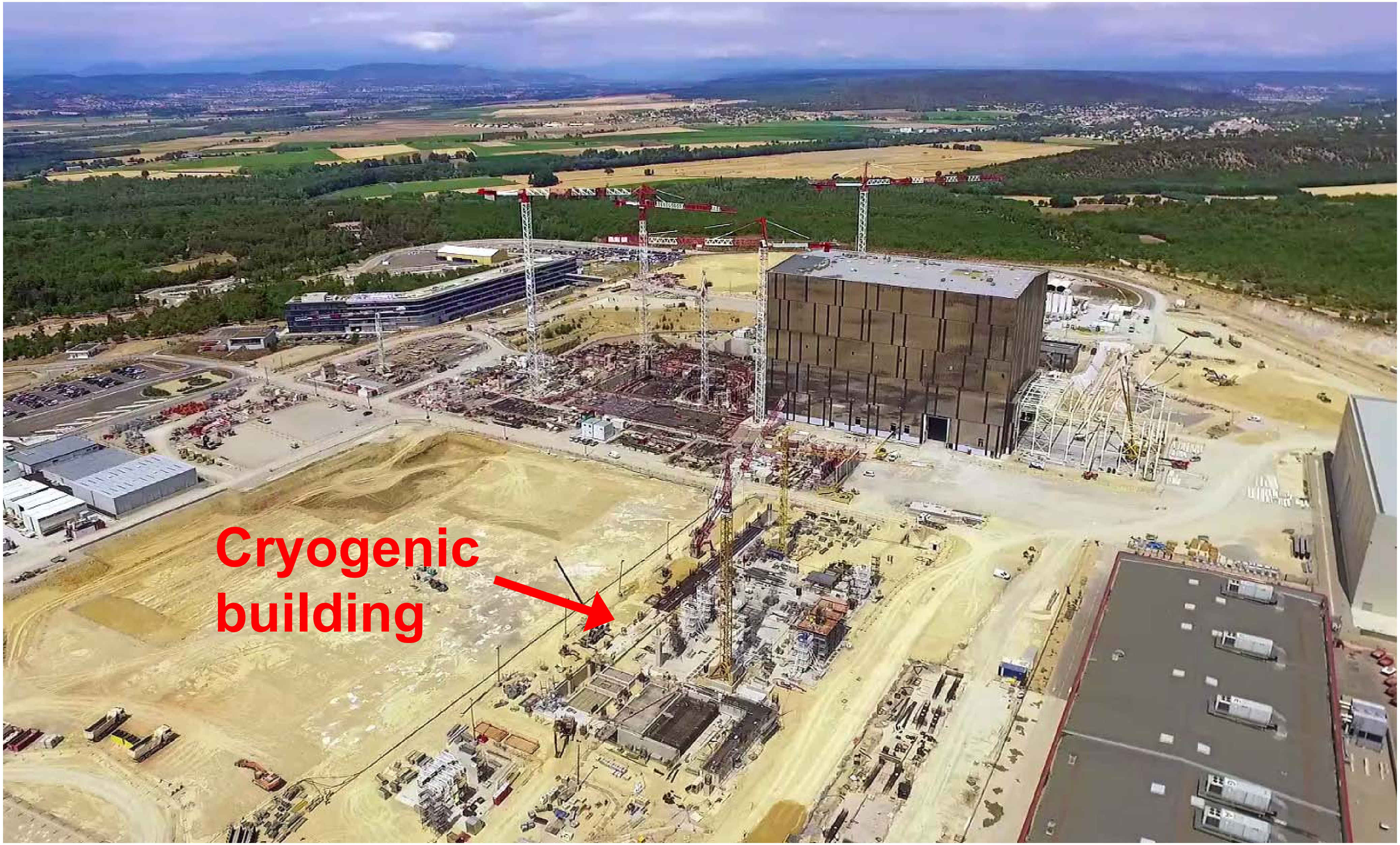
Assembly hall view from rear

Giant crawler crane temporarily installed on site in June to lift the elements of the Assembly Hall travelling cranes into place.

Latest aerial photos of construction site

July 11 2016

Latest aerial photos of construction site



July 11 2016

Component transport

For heaviest components: vacuum vessel sectors, toroidal field coils, PF coils 1,6

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

ITER itinerary ~104 km by road + 32 km by barge

Component transport

352 wheel test convoy carrying 800 ton load trialled in September 2013 and March/April 2014

2 power generators developing 730 horse power

Components now arriving regularly

Double convoy bringing two of the four 47-ton girders for the Assembly Hall cranes along the roads from the Mediterranean Sea to the ITER site: 5 km/hour

Where do you (the young people) fit in?

- In the years up to end construction (~2025)
  - Best way to support ITER is through the Members facilities → PhD, postdocs, R&D
  - Only a handful of physicists on the ITER team until just before operation begins
  - "Monaco fellows" (postdocs) every 2 years
  - Next application round ~Feb/Mar 2018
  - Several 6 month internships possible per year for undergraduate/masters students
  - Collaborative Phd opportunities (new, and limited in number)

Where do you (the young people) fit in?

Exploitation phase

- ITER becomes the focus of worldwide magnetic confinement research
- Will require a very large team of physicists/engineers familiar with tokamaks/fusion technology

So please stay in the field long enough to take part!

Summary

ITER is one of the most challenging and innovative scientific projects in the world today

- Demonstration of controlled fusion power production is one of the great scientific enterprises of the 21st century
- ITER is a burning plasma experiment, a major technology R&D programme and a ground-breaking international collaboration

ITER construction is making visible progress

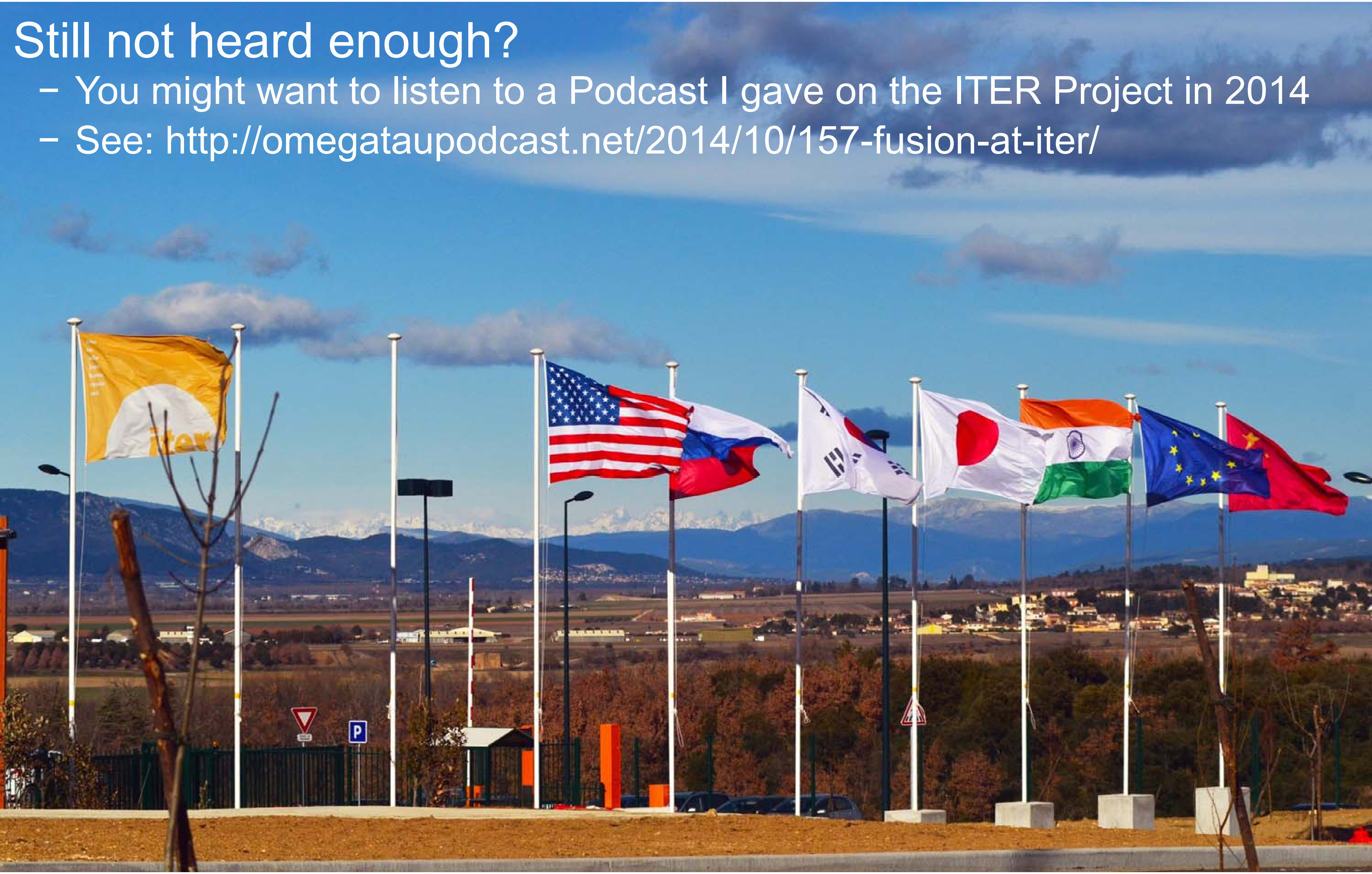
- Construction of the ITER device is advancing both on-site and in Members' industries

Significant progress has been made in recent years within fusion community to address key ITER Physics R&D issues, but much remains still to be done

- Experiments, theory and simulations

Still not heard enough?

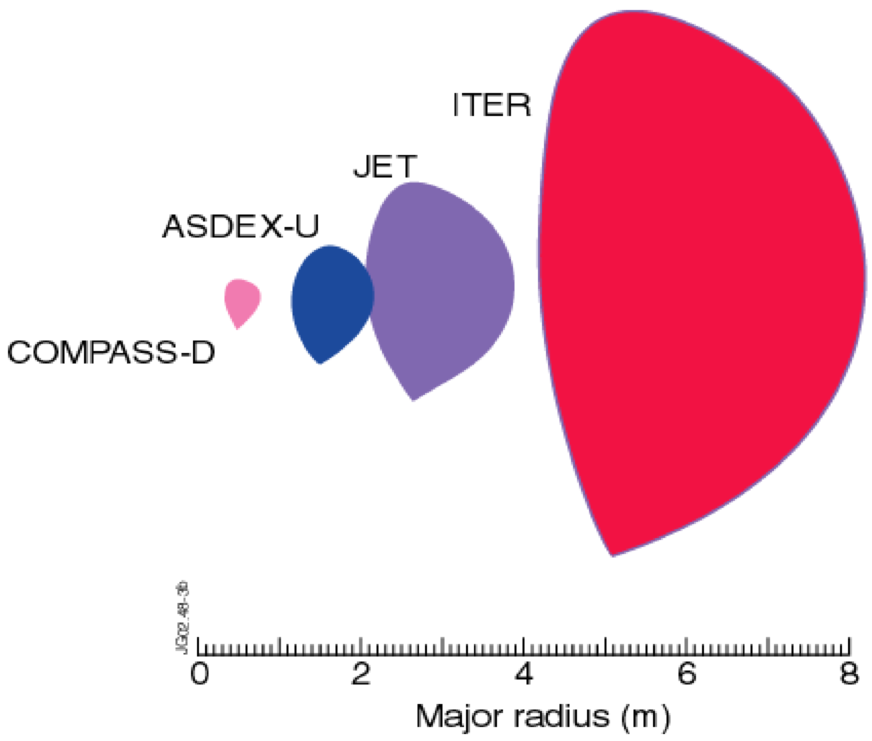
- You might want to listen to a Podcast I gave on the ITER Project in 2014
- See: http://omegataupodcast.net/2014/10/157-fusion-at-iter/

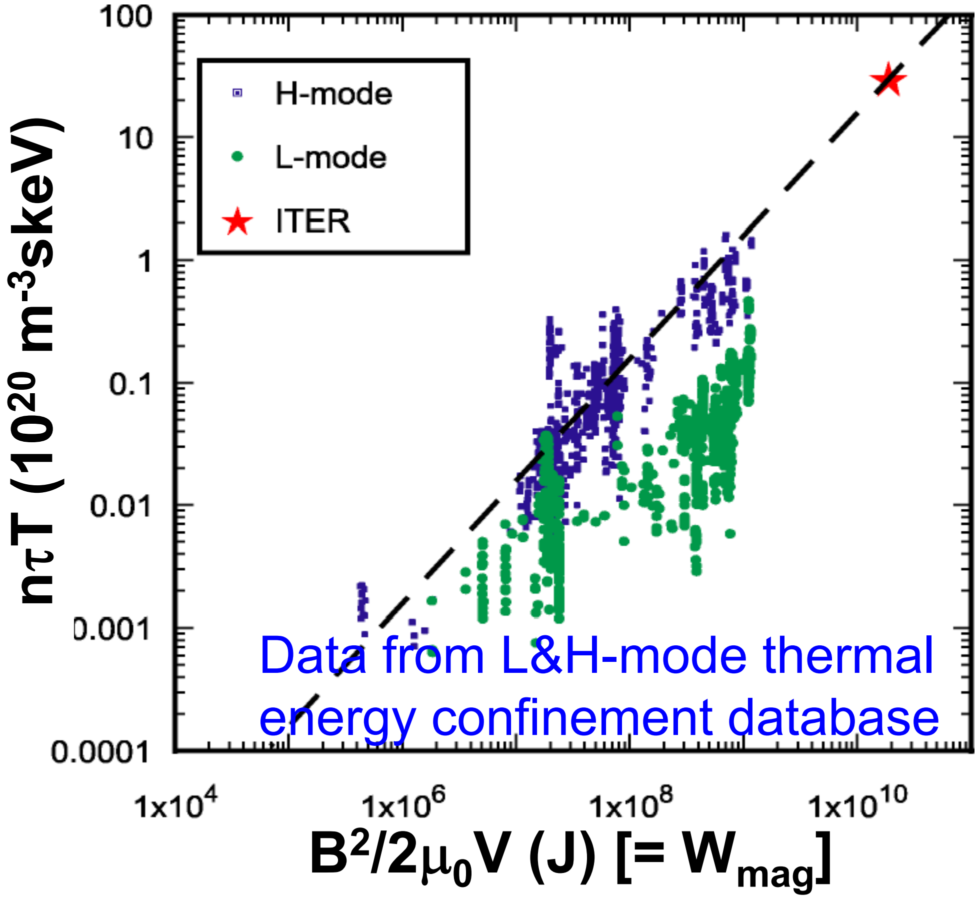


Thank you

Reserve

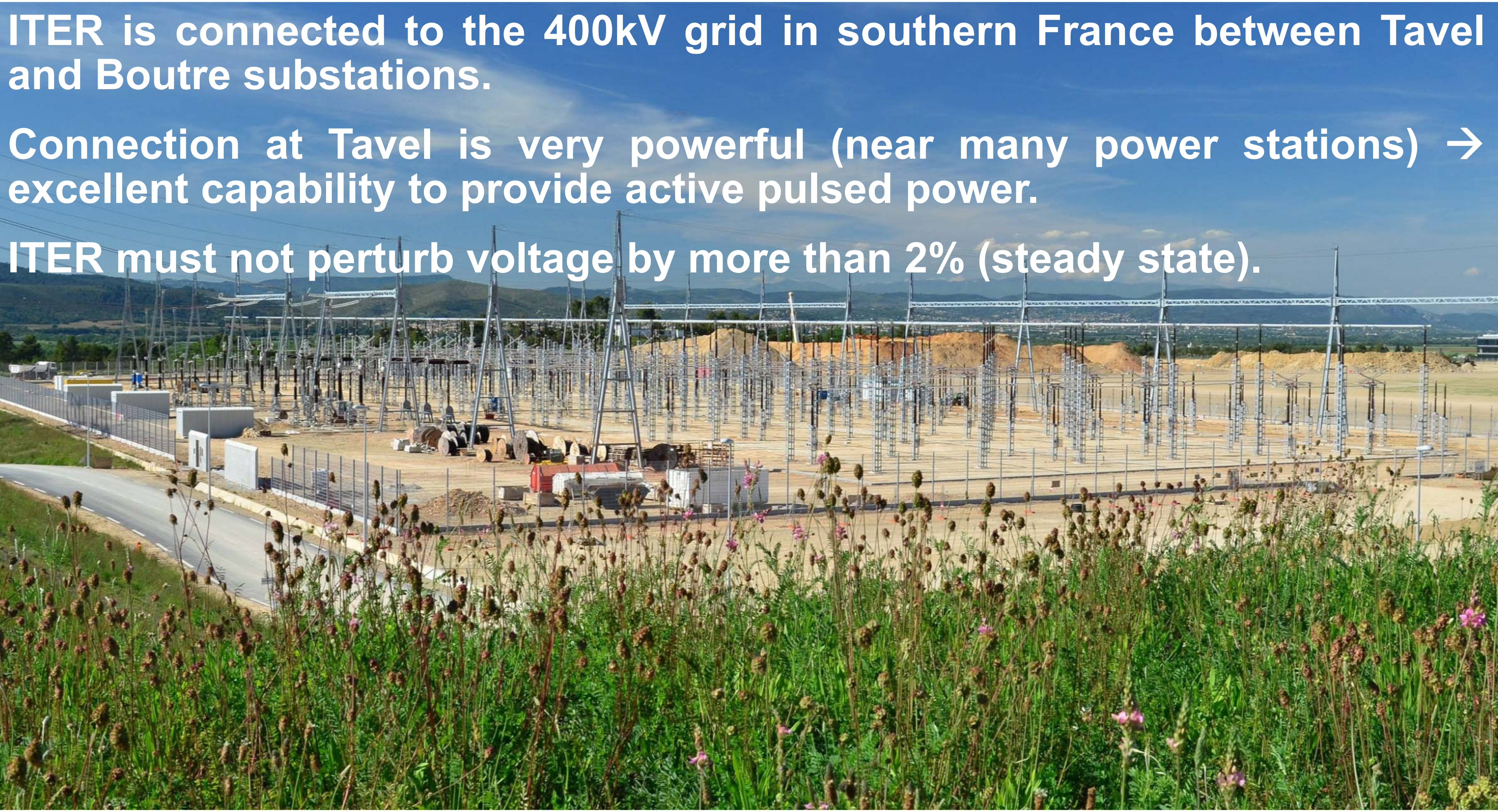
How big should ITER be?





- Confinement scaling studies provide a robust approach to determining ITER's size
  - Best performance (in terms of $n\tau T$) from all machines versus stored magnetic field energy extrapolates to the required $n\tau T$ on ITER at the ITER field energy

Electrical supply

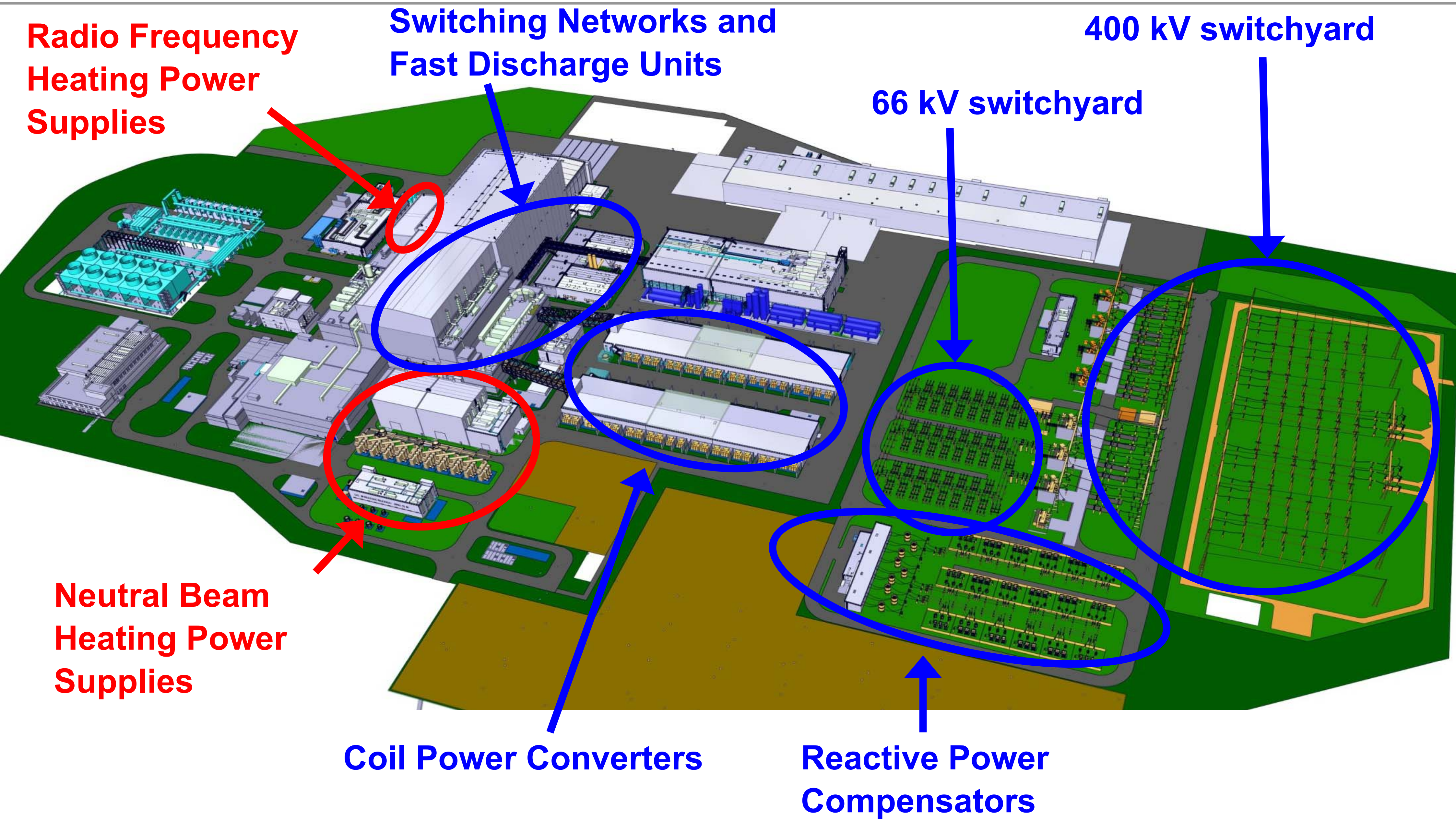


ITER is connected to the 400kV grid in southern France between Tavel and Boutre substations.

Connection at Tavel is very powerful (near many power stations) → excellent capability to provide active pulsed power.

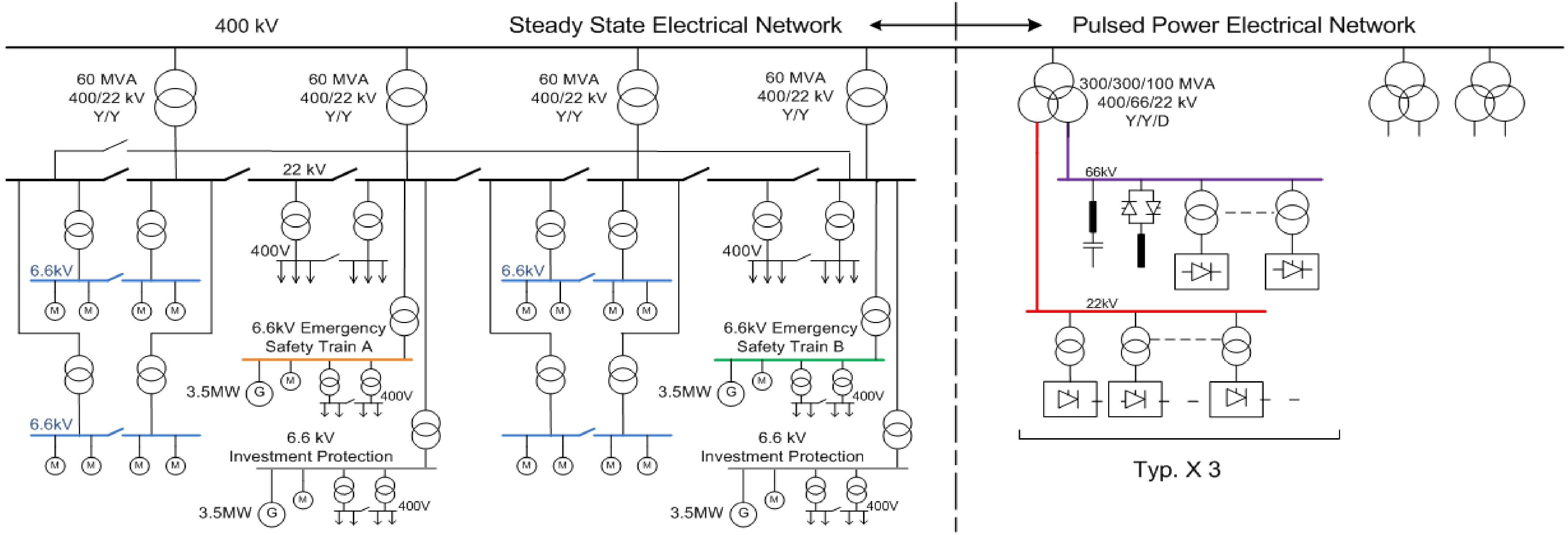
ITER must not perturb voltage by more than 2% (steady state).

Main pulsed power supply components



Electrical Distribution: outline diagram

ITER AC Power System consists of continuous and pulsed supplies:
Steady State Electrical Network (SSEN) and Pulsed Power Electrical Network (PPEN)



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

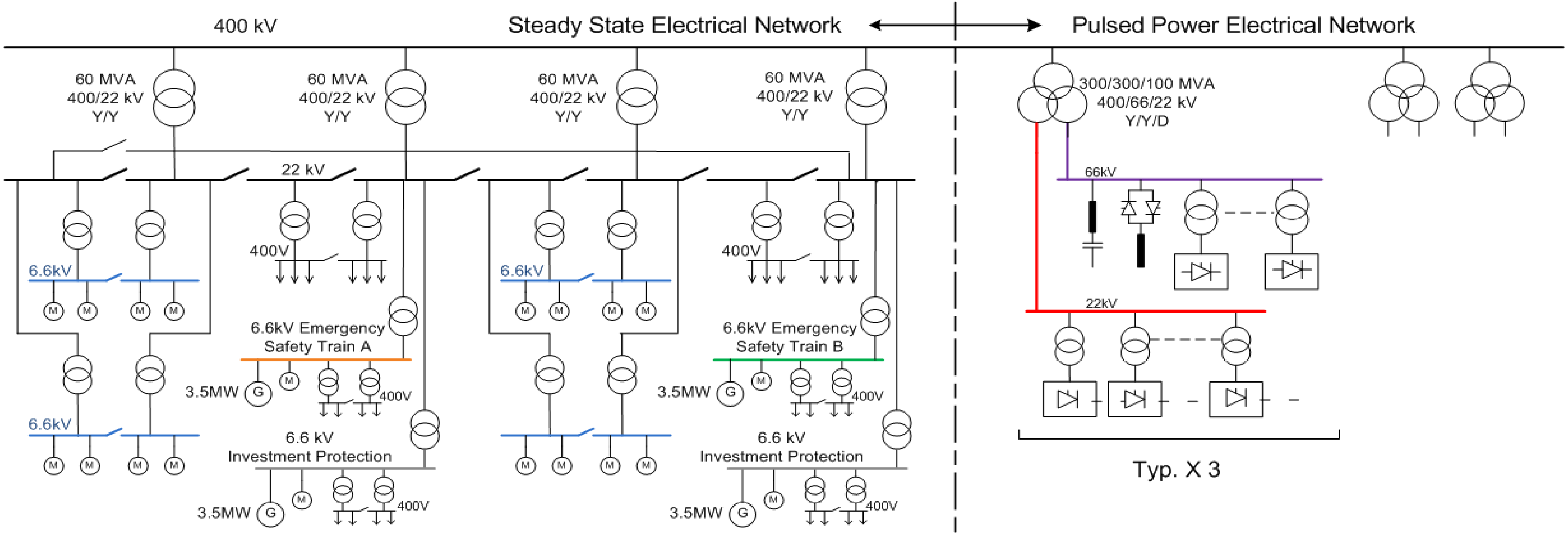
Main consumers:

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

Includes large Static Var Compensators

Electrical Distribution: outline diagram

ITER AC Power System consists of continuous and pulsed supplies:
Steady State Electrical Network (SSEN) and Pulsed Power Electrical Network (PPEN)



Total power to be distributed by the SSEN is about twice that of a 1.6 GW, third generation (EPR), nuclear power plant (but is a standard industrial electrical power system)