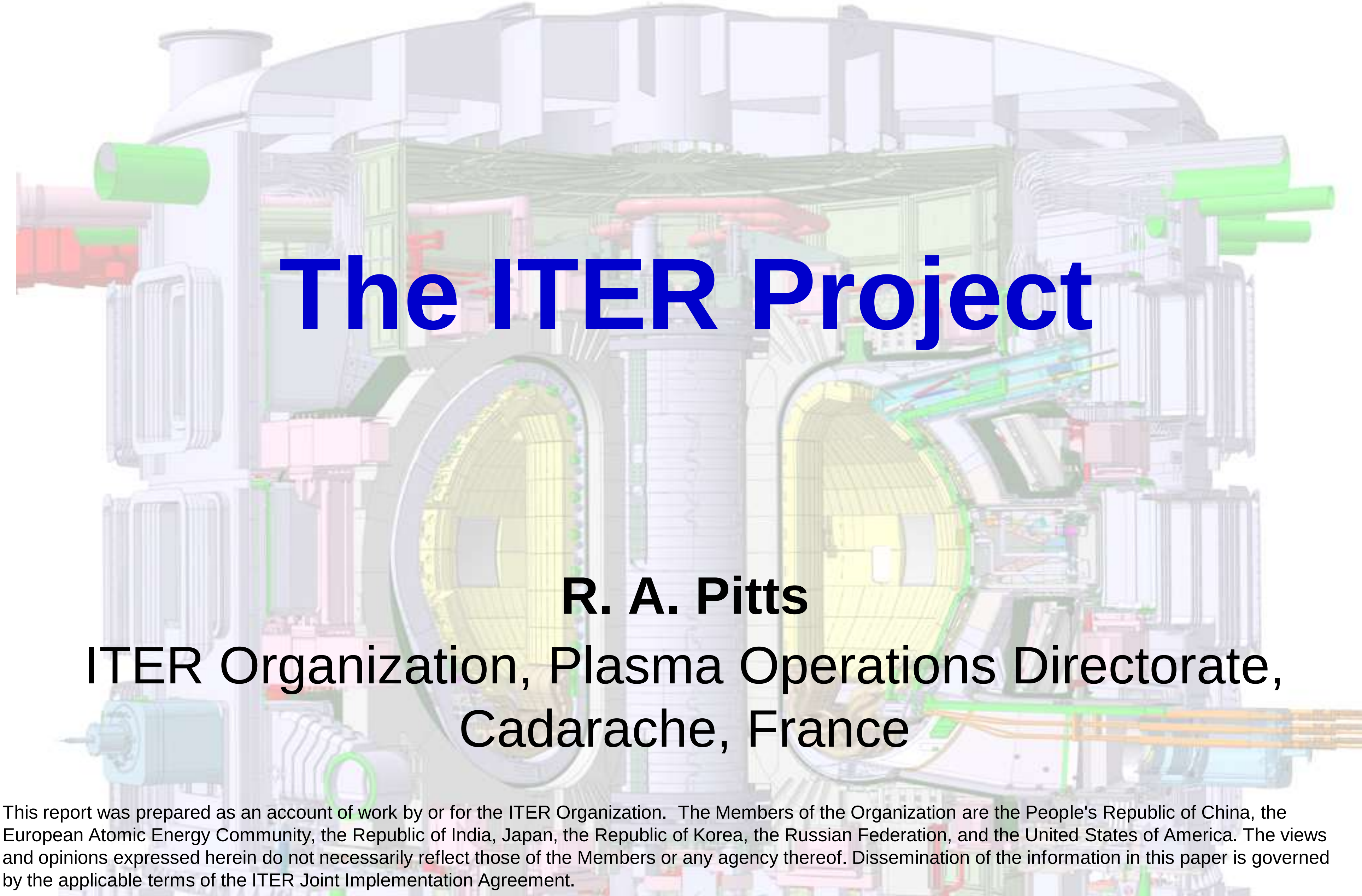


The ITER Project

R. A. Pitts

ITER Organization, Plasma Operations Directorate,
Cadarache, France

What is ITER?

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

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

Before we start – a digression on the ITER site preparations

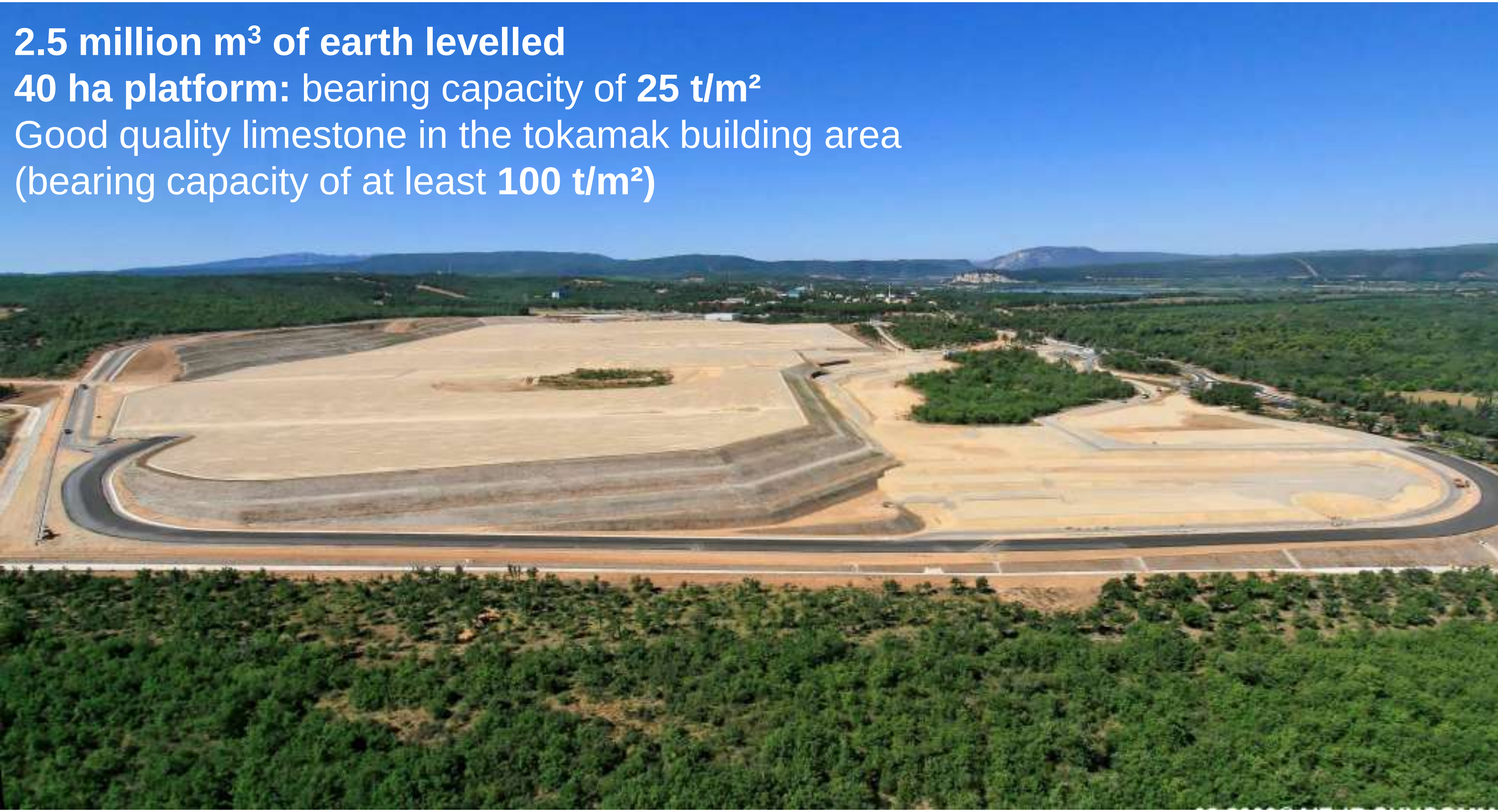
The site in 2005

And after 4 year's work

2.5 million m³ of earth levelled

40 ha platform: bearing capacity of **25 t/m²**

Good quality limestone in the tokamak building area (bearing capacity of at least **100 t/m²)**



On December 22 2010 …..

On December 22 2010 …..

The poloidal field coil winding building – well underway

PF coil building – what it will look like

PF coils are so big that they must be manufactured on-site

Length: 252 m, width: 45 m, height: 20 m

On December 22 2010 …..

On December 22 2010 …..

Office Headquarters

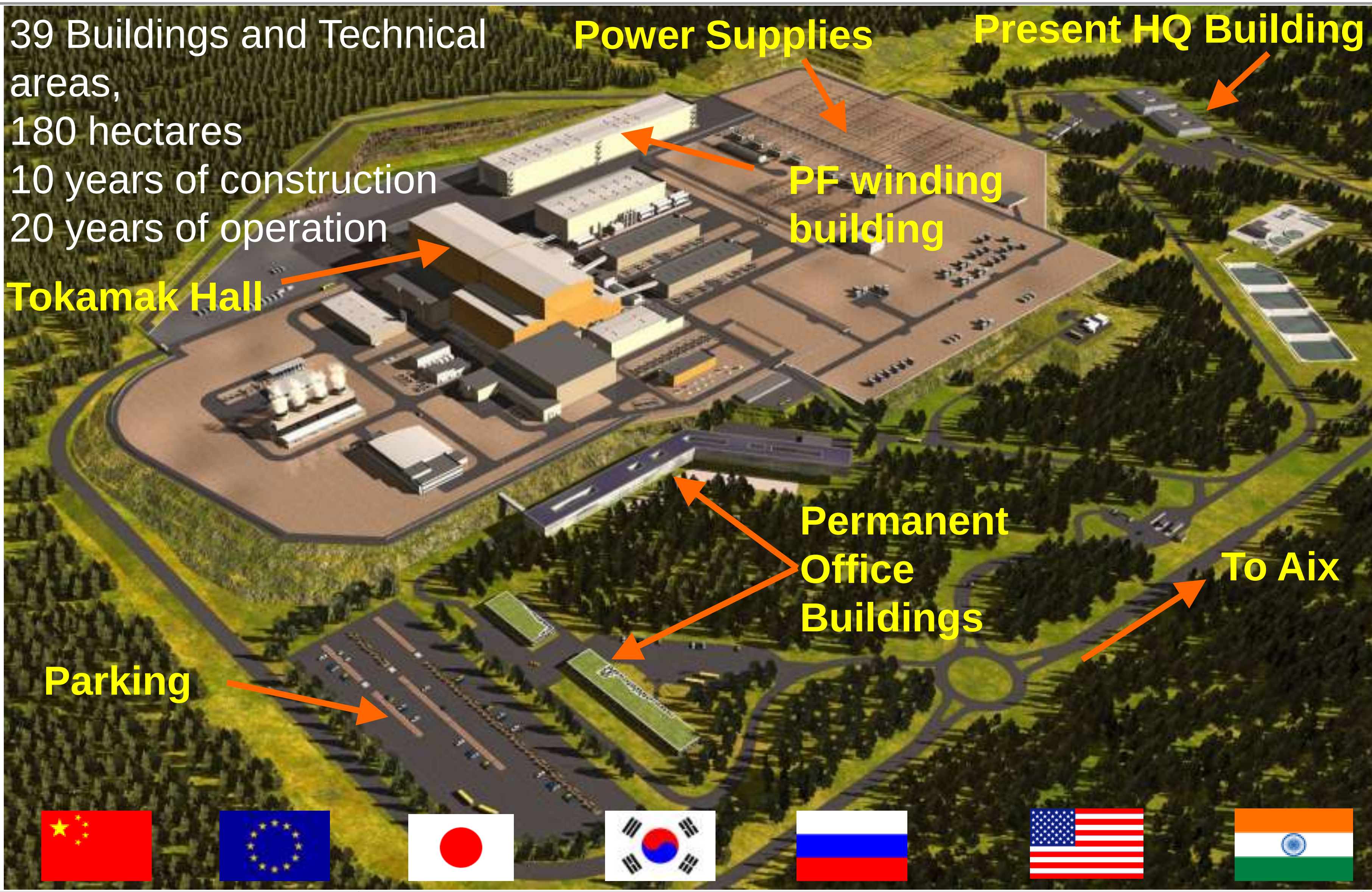
200 m long, capacity around 450 people, 2 year construction

Architect's impression
Rudy Ricciotti, Laurent Bonhomme

Many of us can't wait ……

My office →

The ITER site in 10 years from now



Outline

First, a CAVEAT: the ITER project is a huge undertaking. A short lecture can only give a flavour of what is involved. Physics content will be minimal!

What determines the scale size of ITER?

Key ITER components

Some key operational challenges

Procurement and schedule

Introducing the "ITER standard man": he'll be making a few guest appearances throughout this talk (he's about 1.80 m)

What determines the scale size of ITER?

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’ ($Q \geq 30$)

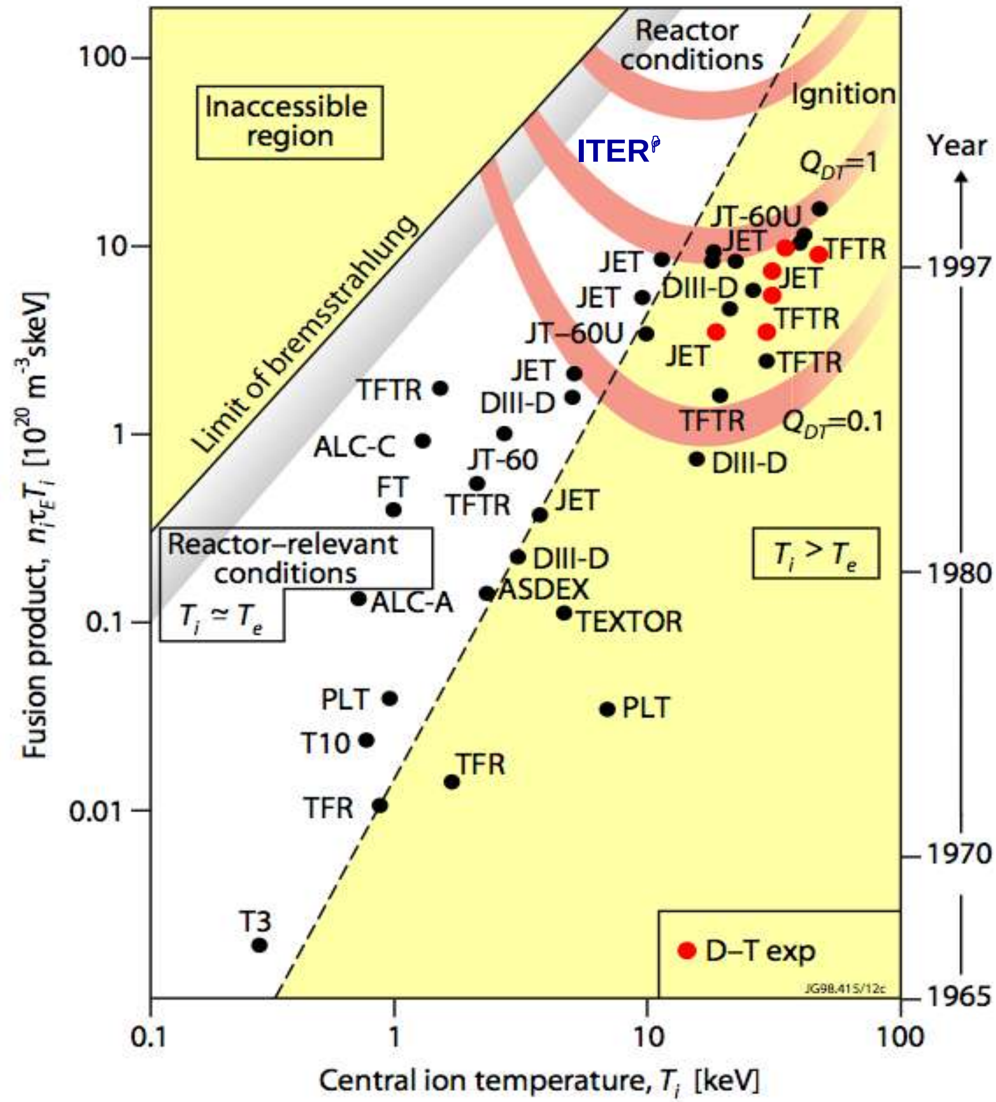
2 Technology

- 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

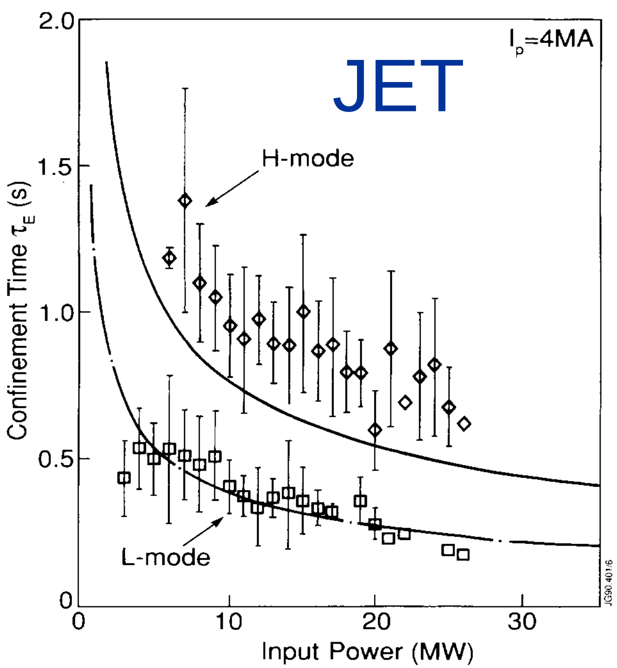
$$Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$$

- Existing experiments have achieved $nT\tau$ values
  ~ $1\times10^{21}\ m^{-3}skeV$
  ~ $Q_{DT} = 1$
- 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 - 500MW for 300 - 500s → Baseline scenario

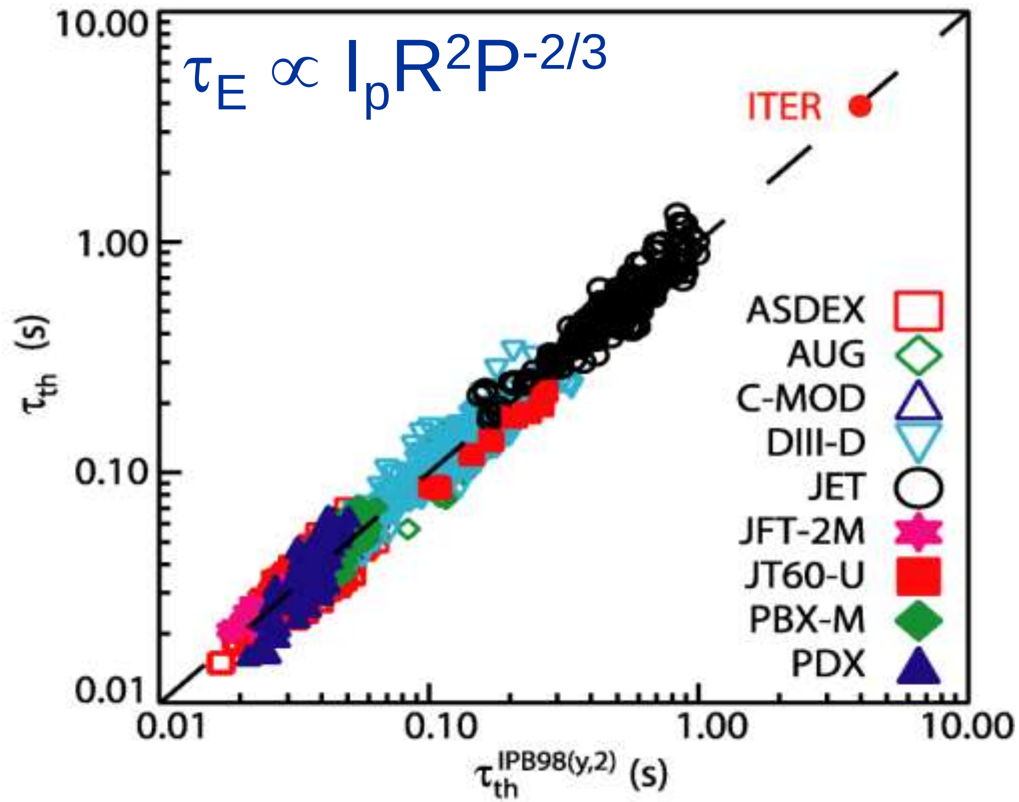


ITER Baseline scenario

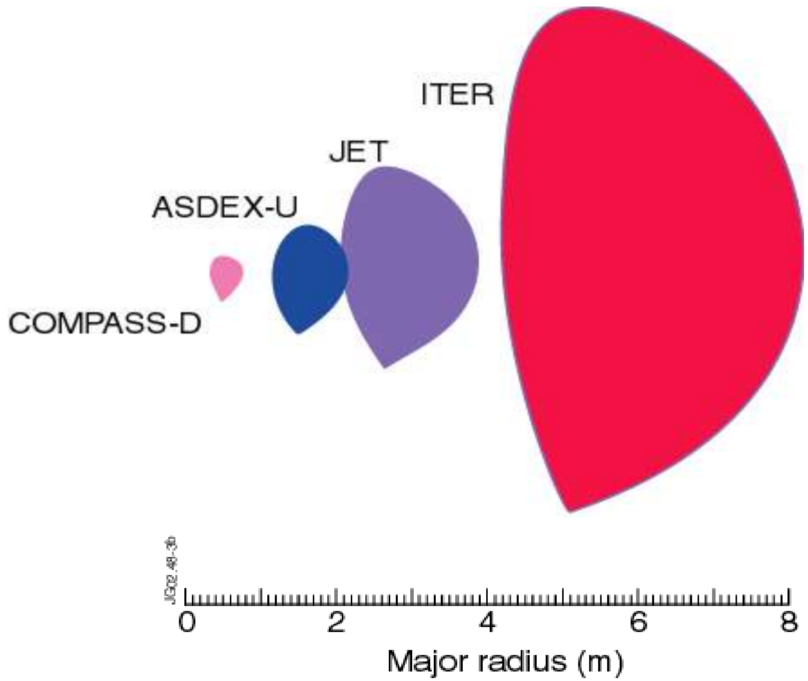
- ELMing H-mode
  - Robust mode of operation (today's tokamaks)
  - Very large multi-machine database provides a scaling prediction for the ITER energy confinement time

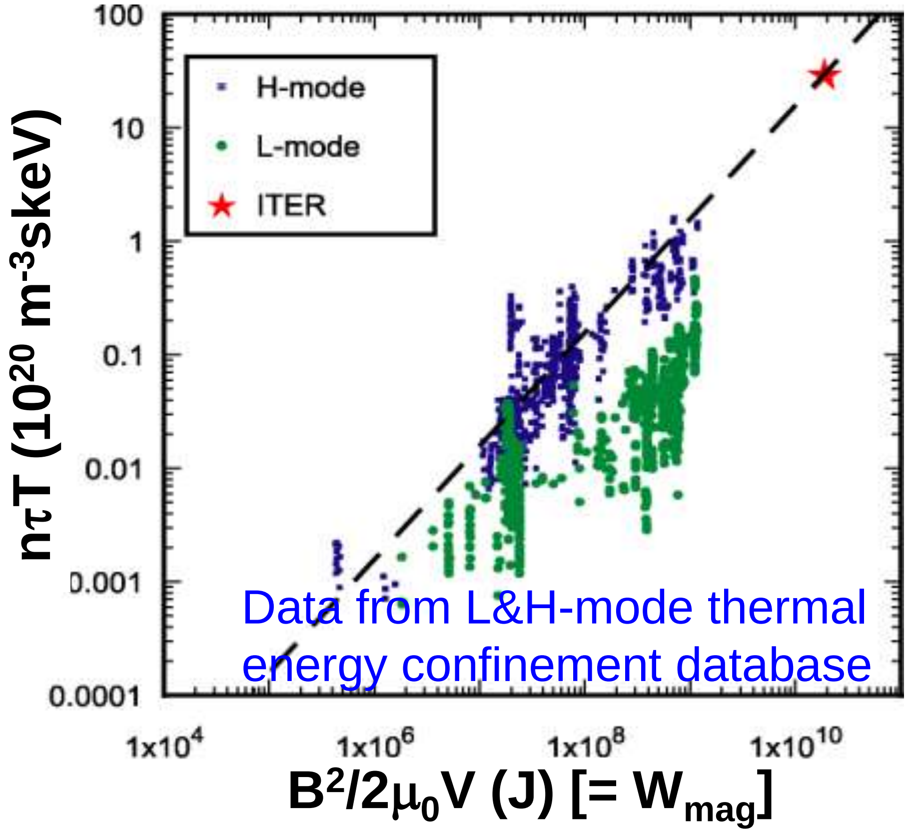


τ_E (H-mode) ~2 x τ_E (L-mode)



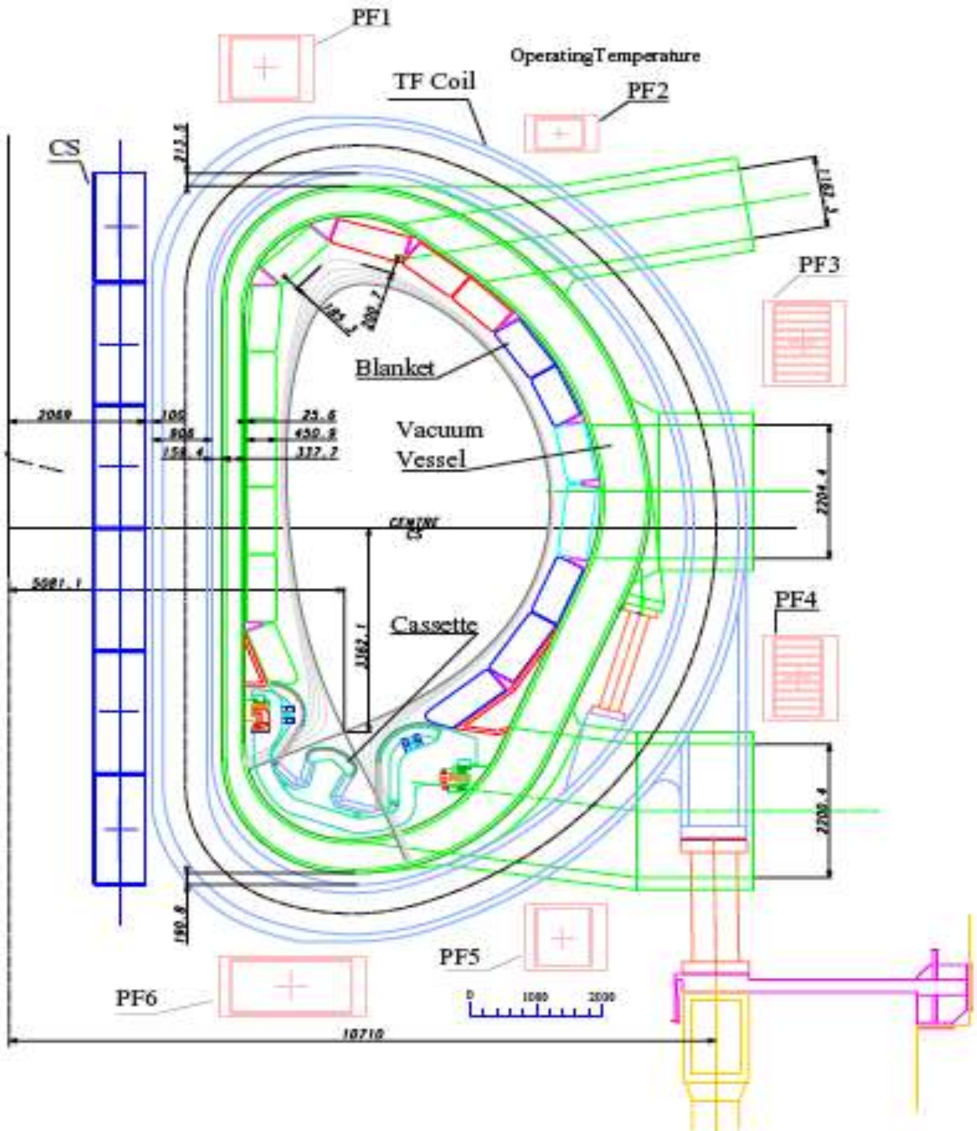
How big should ITER be?





- 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

ITER Design Parameters



	ITER
Major radius	6.2 m
Minor radius	2.0 m
Plasma current	15 MA
Toroidal magnetic field	5.3T
Elongation / triangularity	1.85 / 0.49
Fusion power amplification	≥ 10
Fusion power	~500 MW
Plasma burn duration	300-500 s

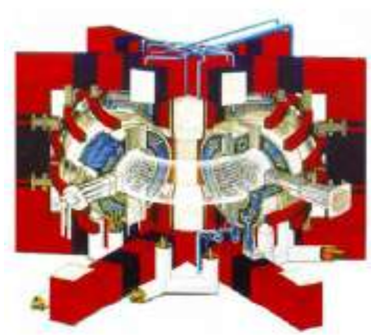
Final size is a compromise between fusion burn requirements, the need for a neutron shielding blanket and cost

- e.g. cost of toroidal field $\propto B^4$

A detailed engineering design for ITER was delivered in July 2001

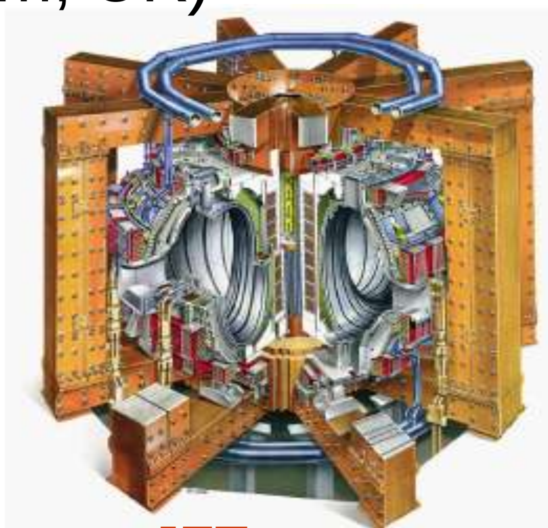
ITER – the biggest tokamak ever built

Many tokamaks have been built over the past 60 years.
ITER will be twice as big as the biggest tokamak still operating (JET, Culham, UK)



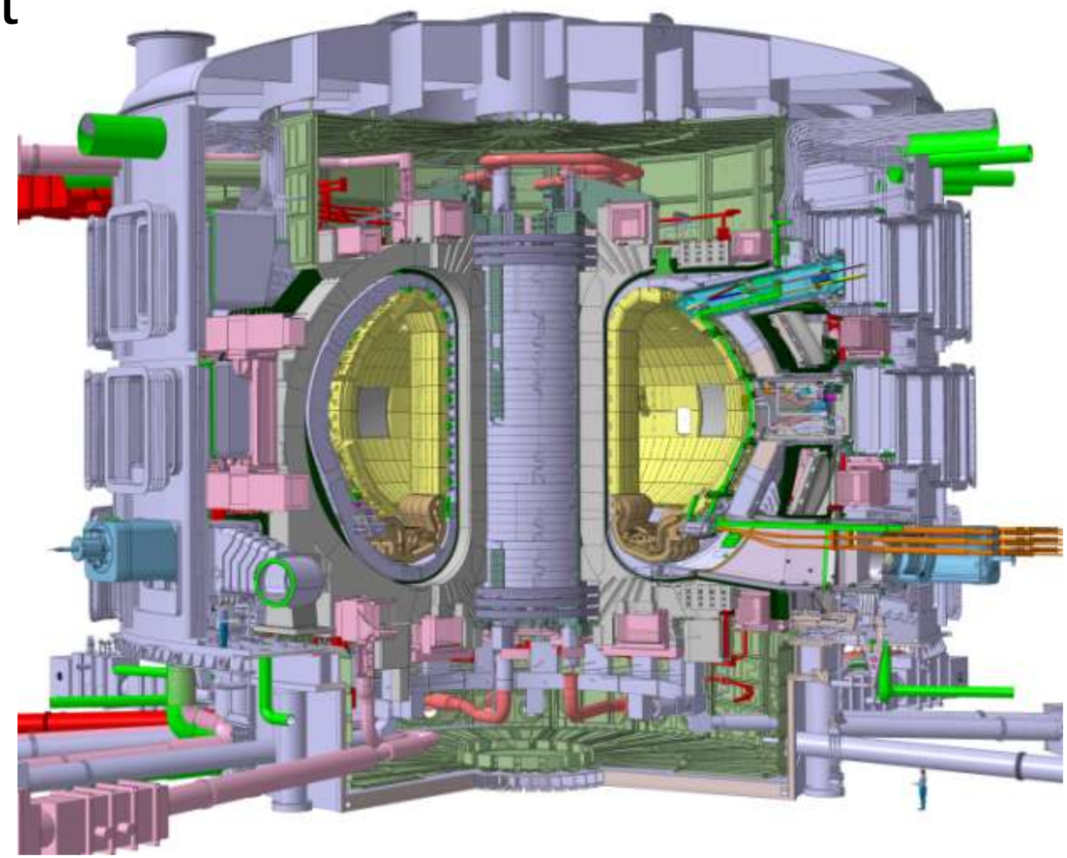
Tore Supra

V_{plasma} 25 m^3, I_p ~ 1 MA
P_{fusion} 0 MW
t_{plasma} ~ 400 s



JET

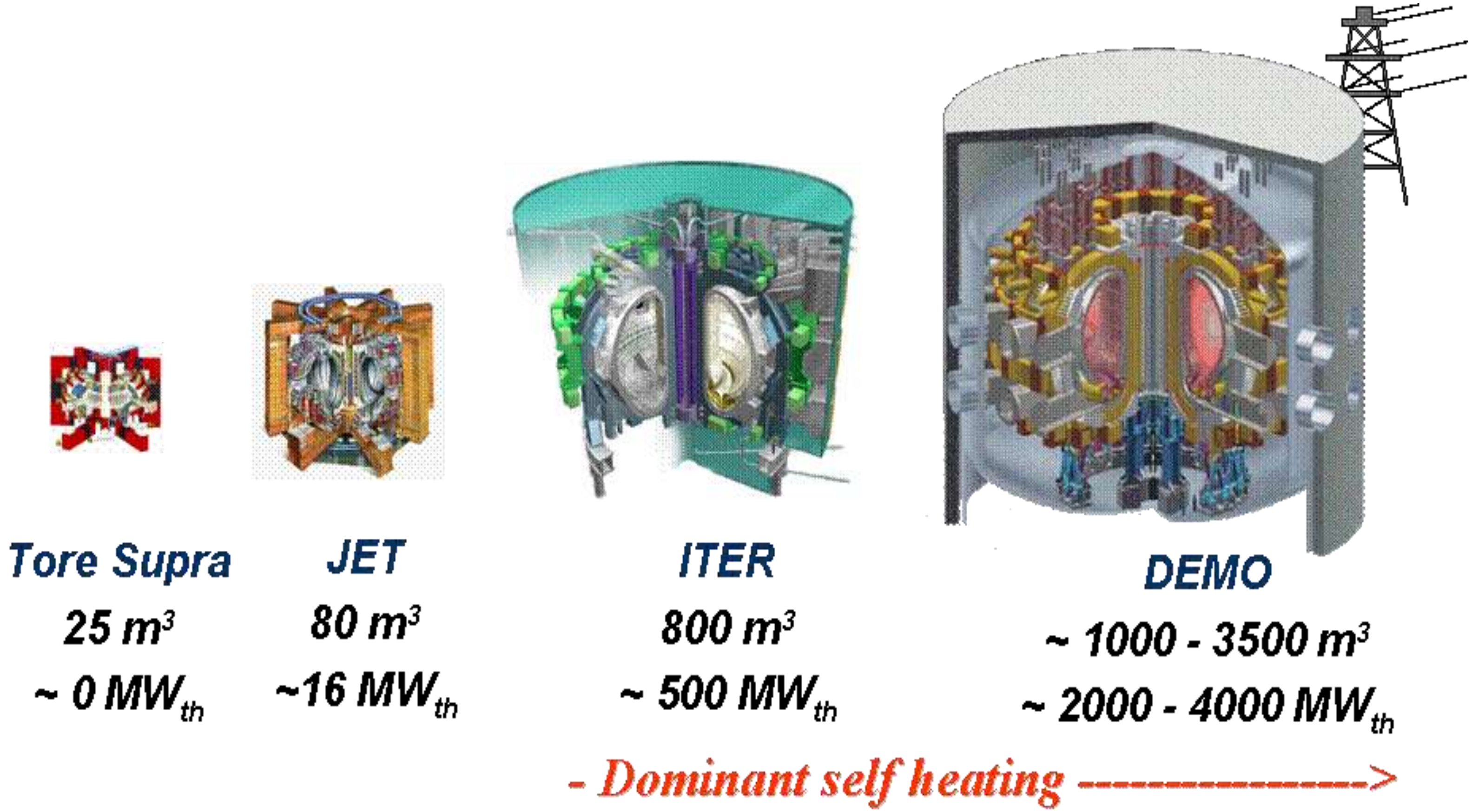
V_{plasma} 80 m^3, I_p ~ 3 MA
P_{fusion} ~16 MW, 1s
t_{plasma} ~30 s



ITER

V_{plasma} 830 m^3, I_p = 15 MA
P_{fusion} ~500 MW, 300 – 500 s, Q = 10
t_{plasma} ~ 600 – 3000 s

But ITER is still an experiment ….

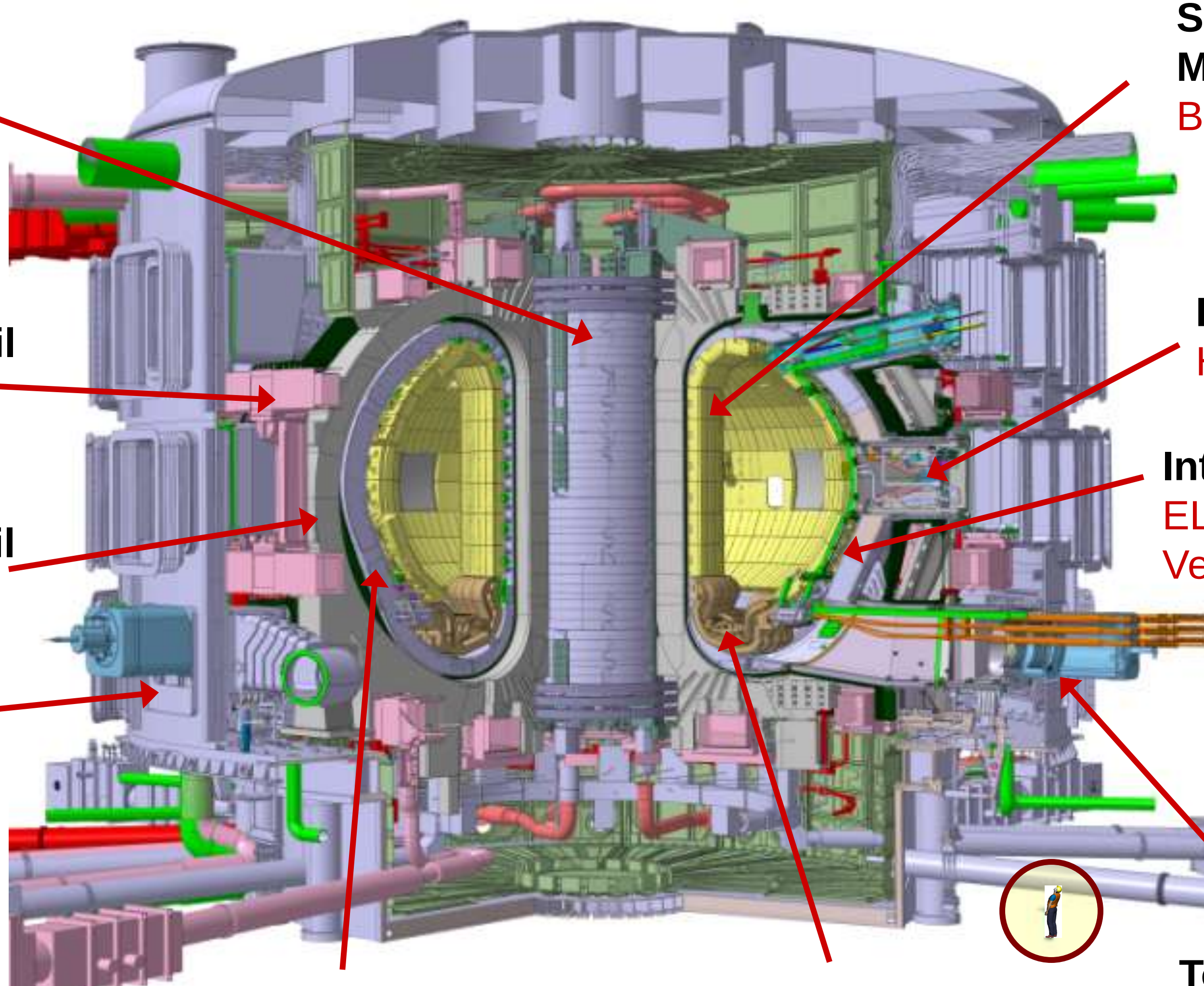


Must show us the way towards DEMO reactors at 2-4 GW

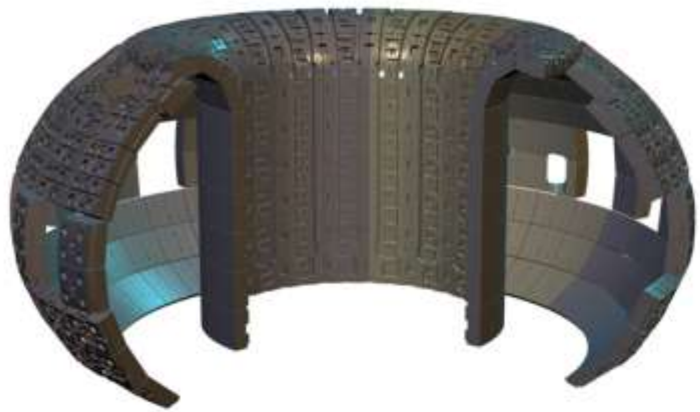
Without this step reactors cannot become a reality

Key ITER components

ITER – main features



From the centre outwards



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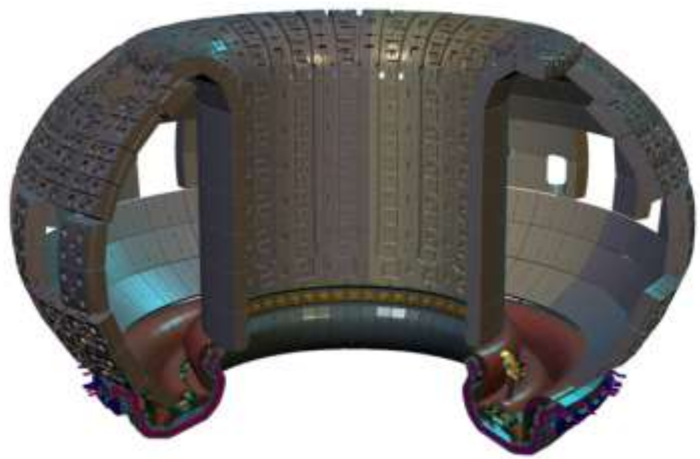

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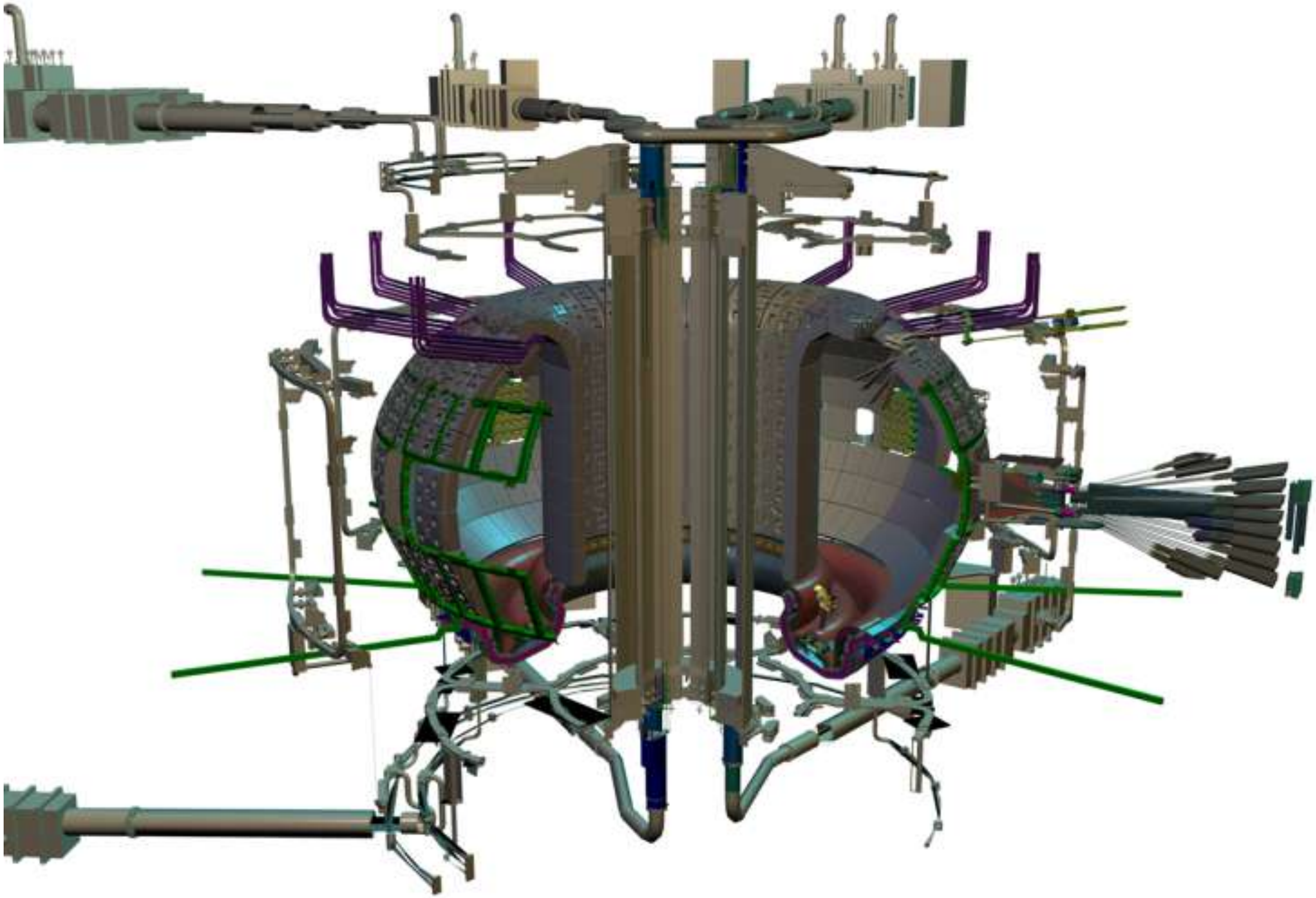

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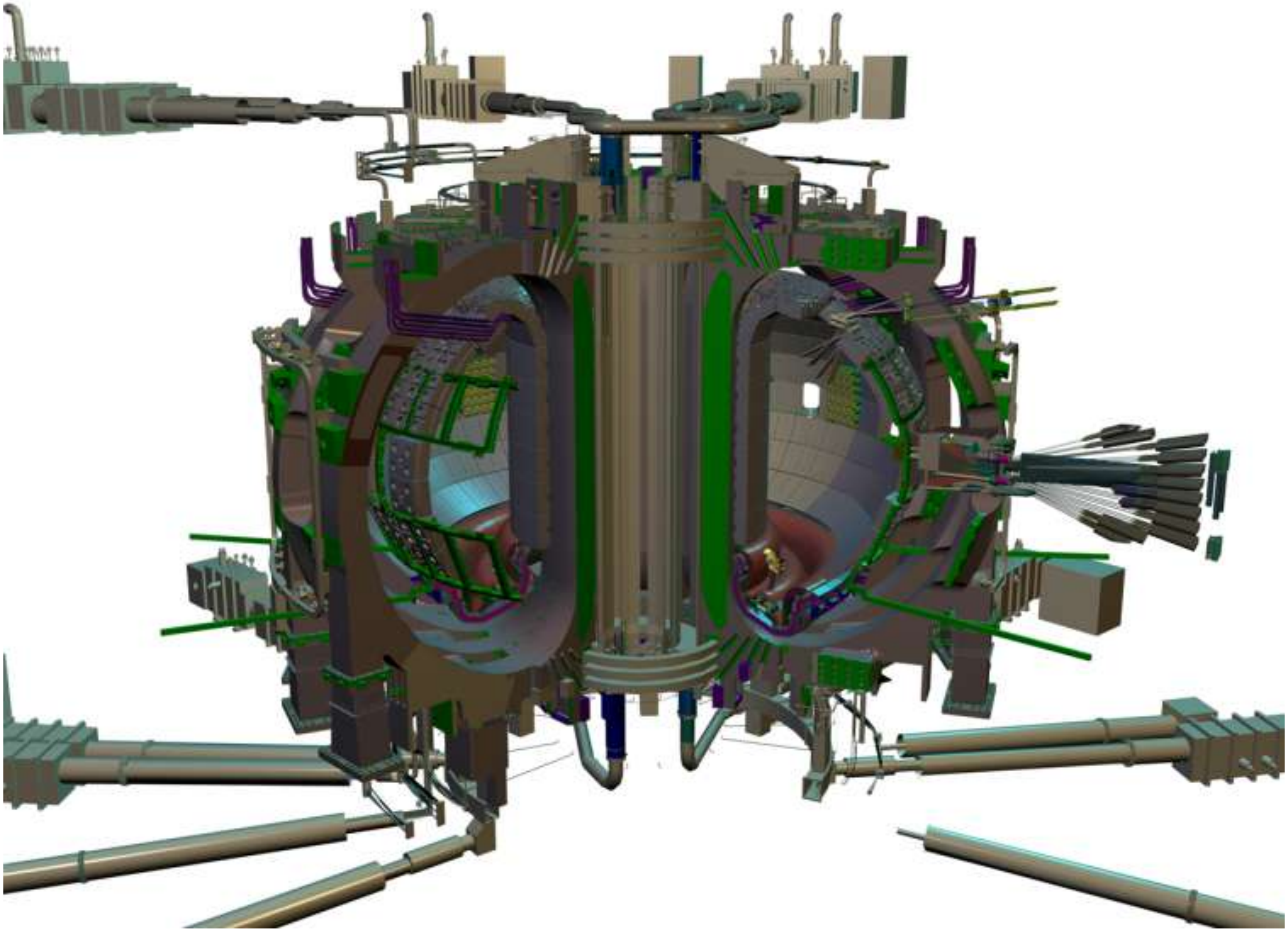

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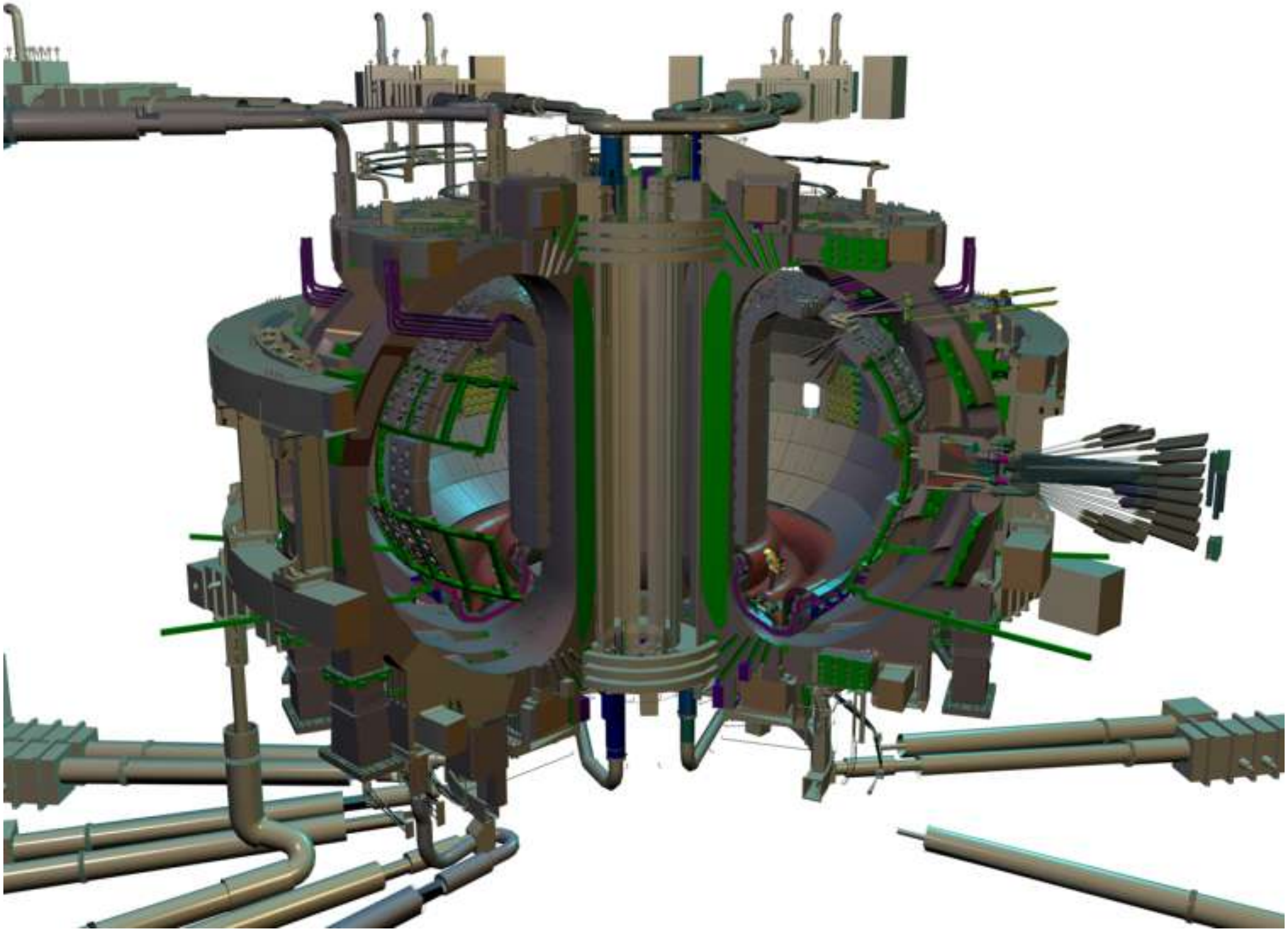

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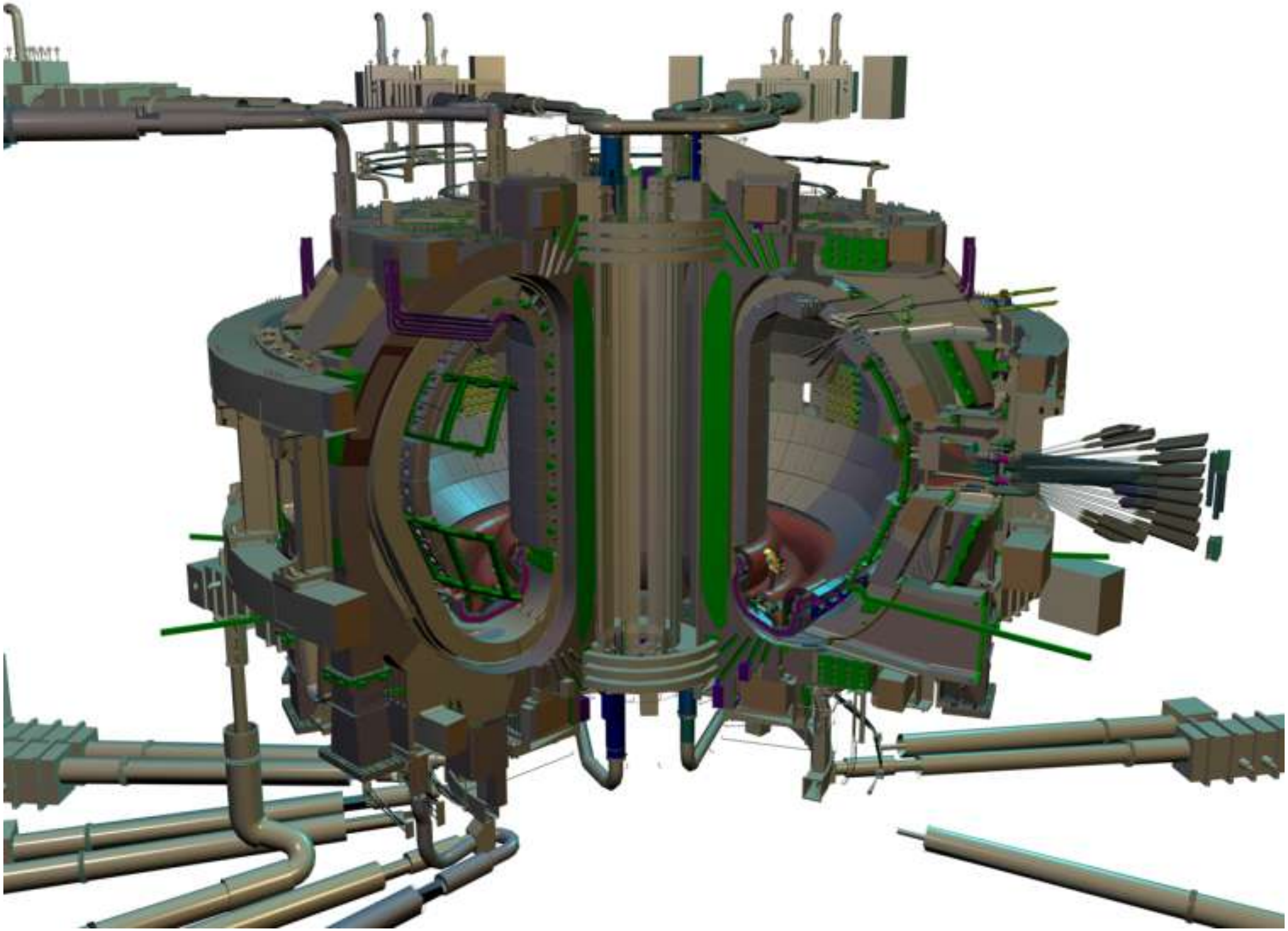

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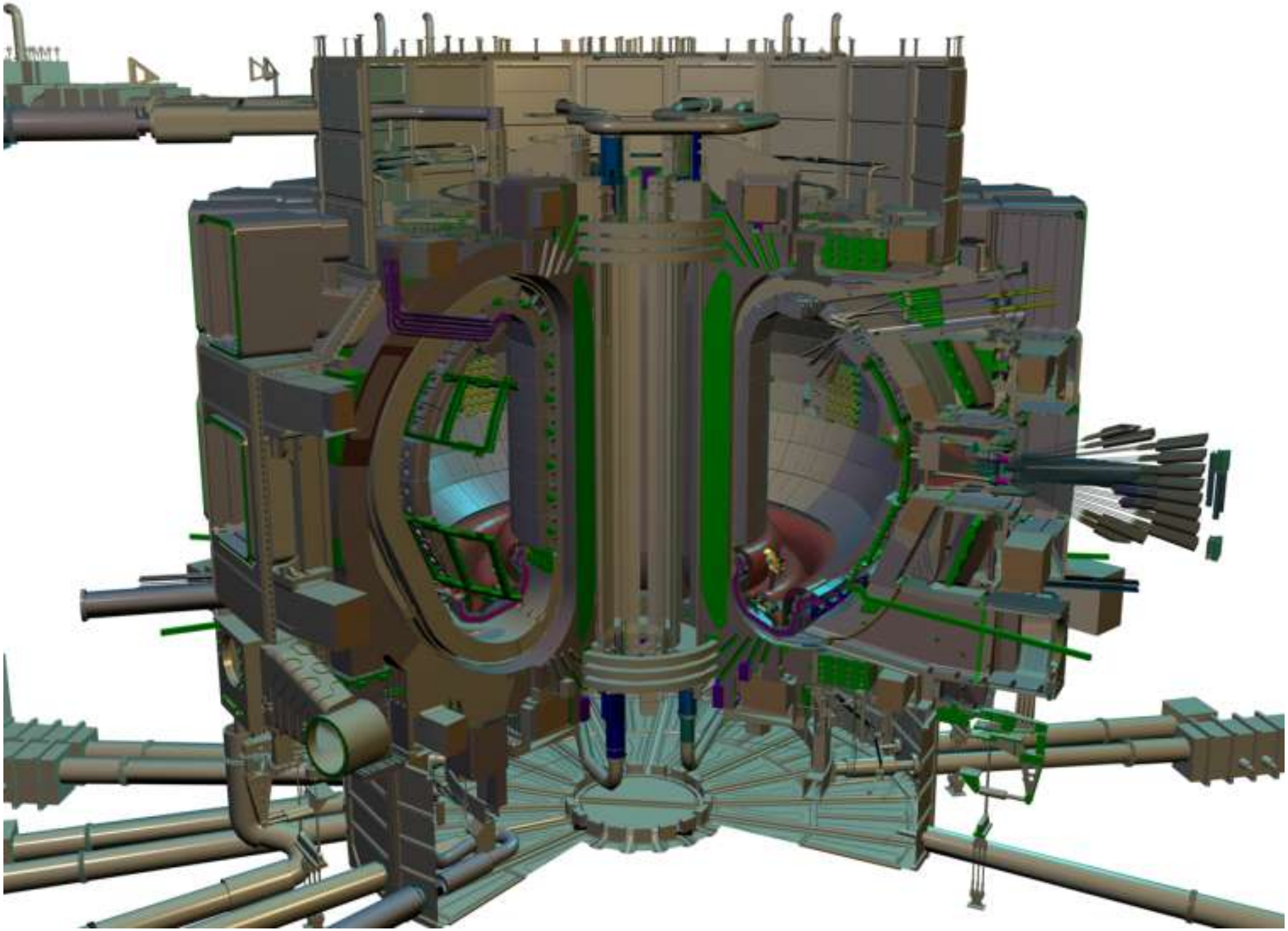

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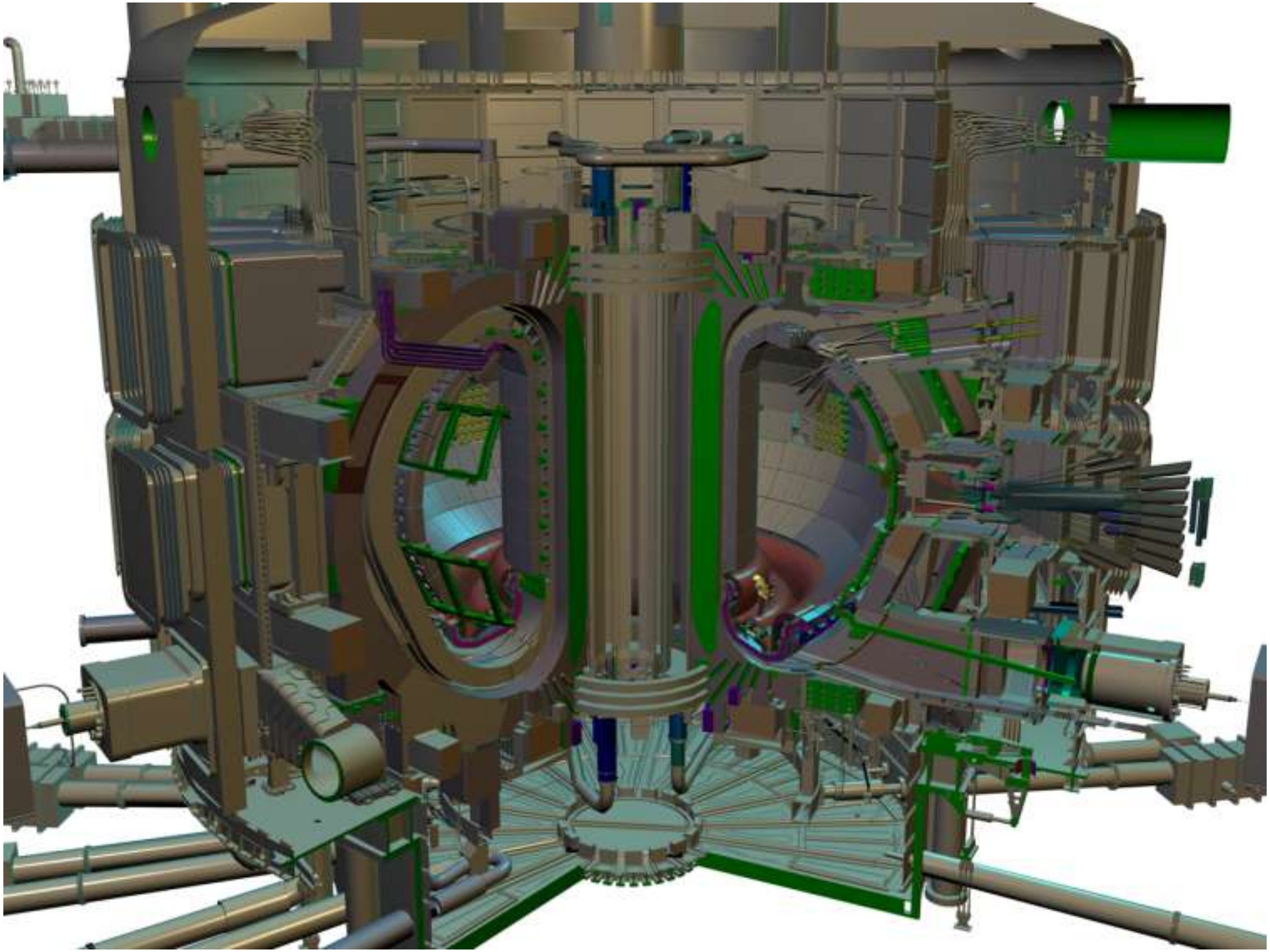
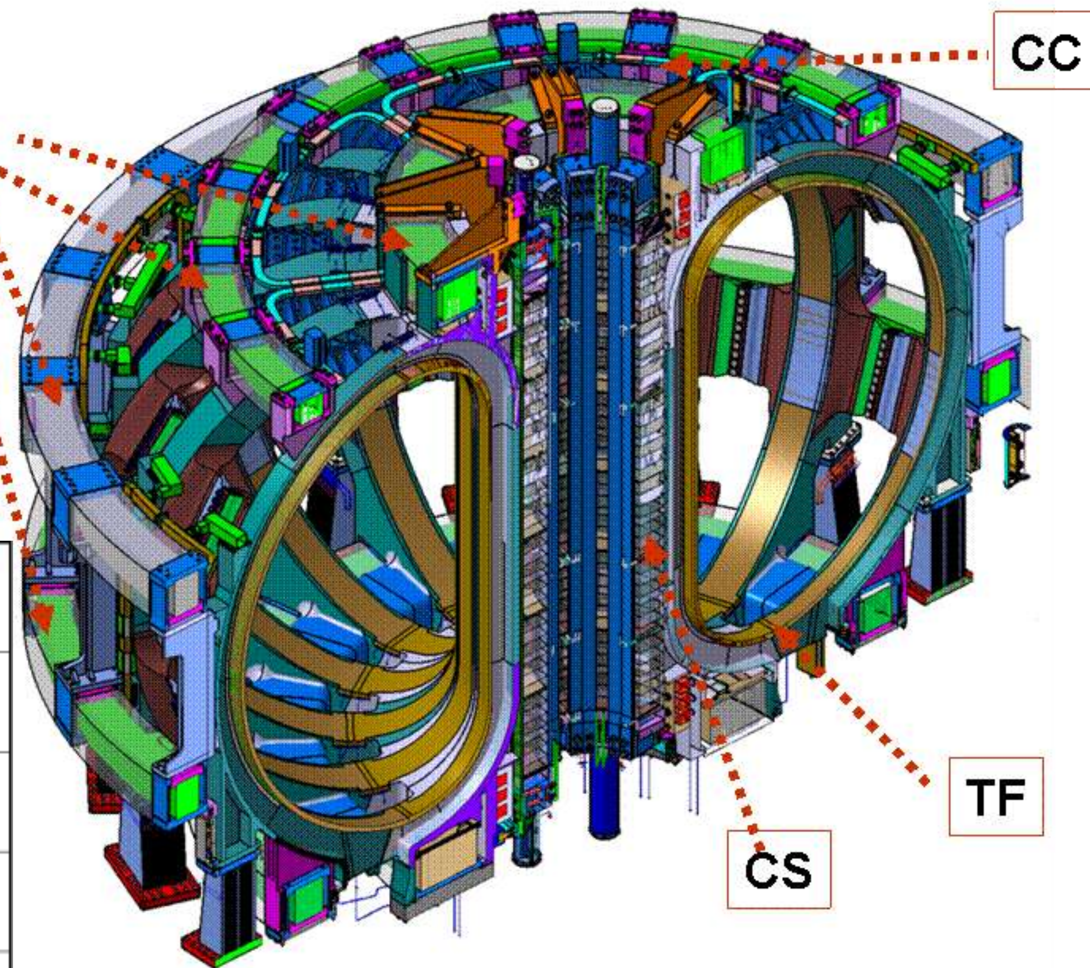


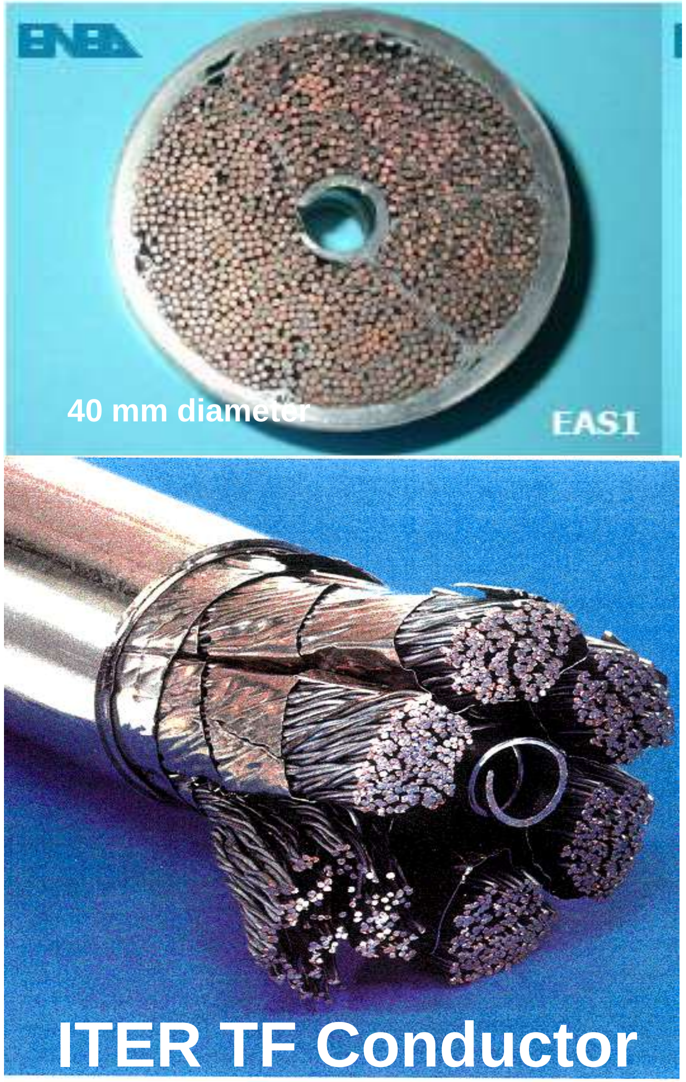
ITER - Magnet Systems

- 48 superconducting coils
  - 18 Toroidal Field coils
  - 6 Central Solenoid modules
  - 6 Poloial 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 conductor procurement

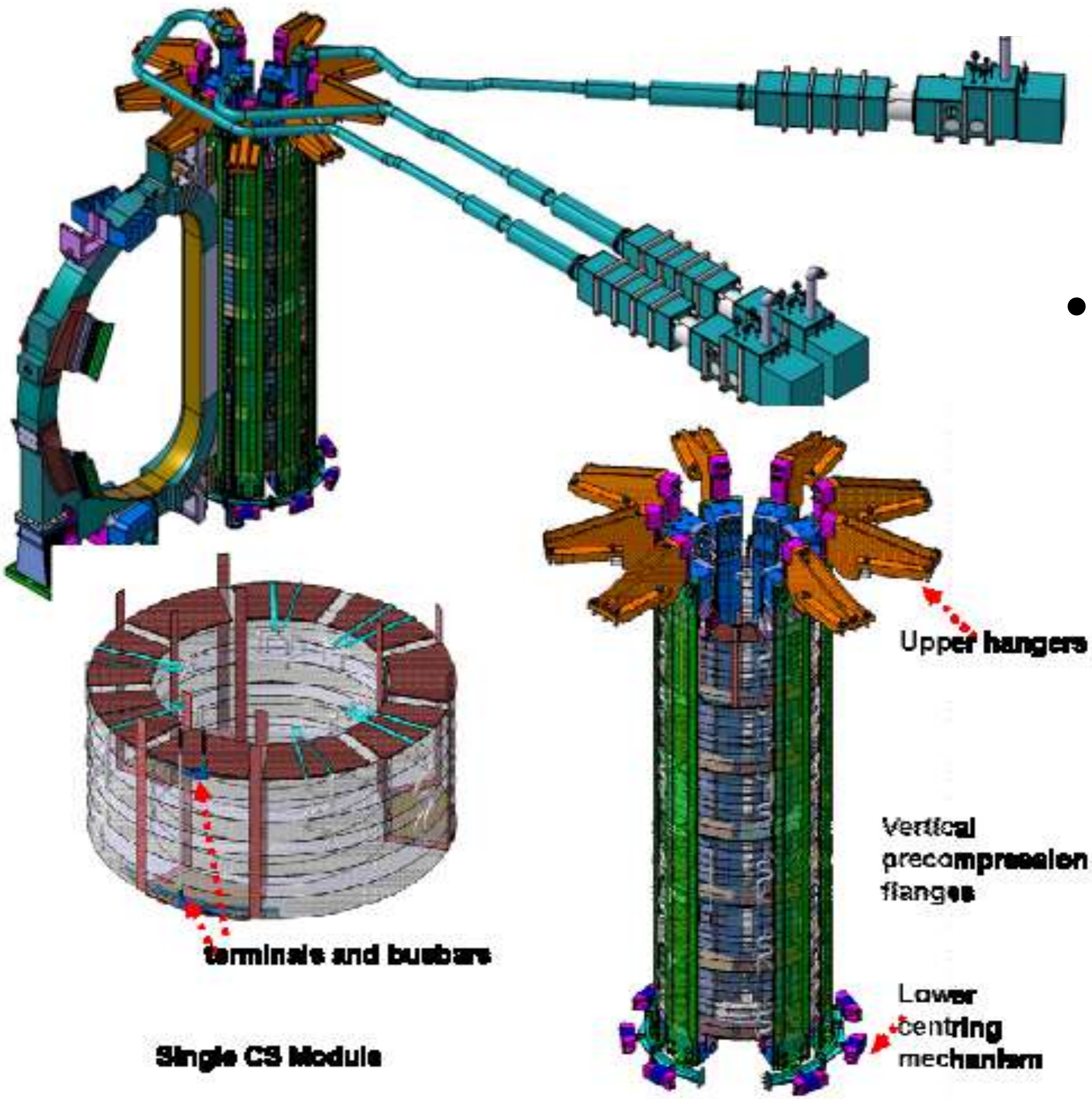


Facts

- ~90 km / 400 tonnes of Nb_3Sn conductor (largest such superconductor procurement in history)
- ~150,000 km of strand
- Operates at ~5 Kelvin
- 11.8 T peak field
- 68 kA peak current in coils

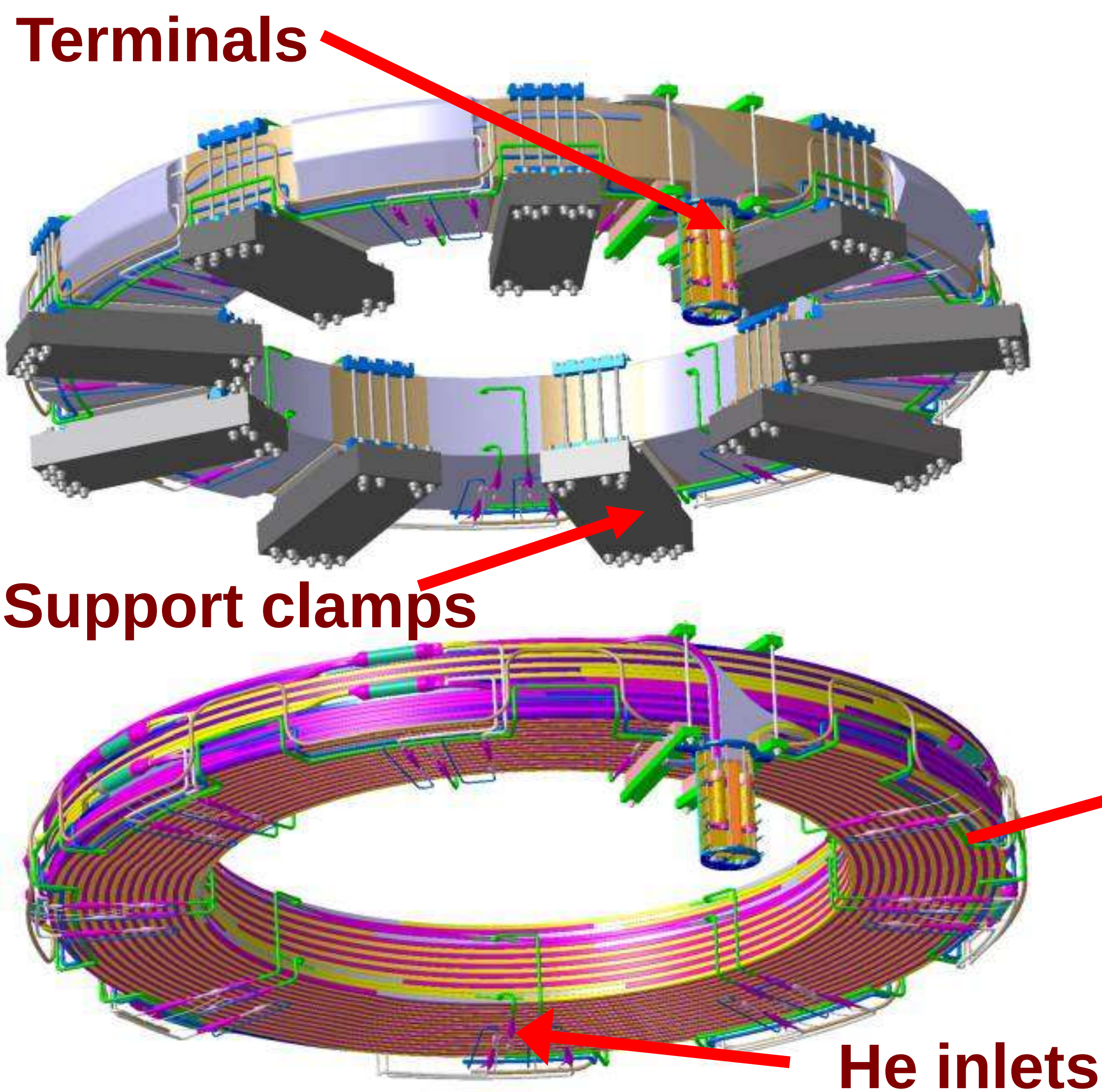
Manufactured by EU, JA, RF, CN, KO & US

Central Solenoid



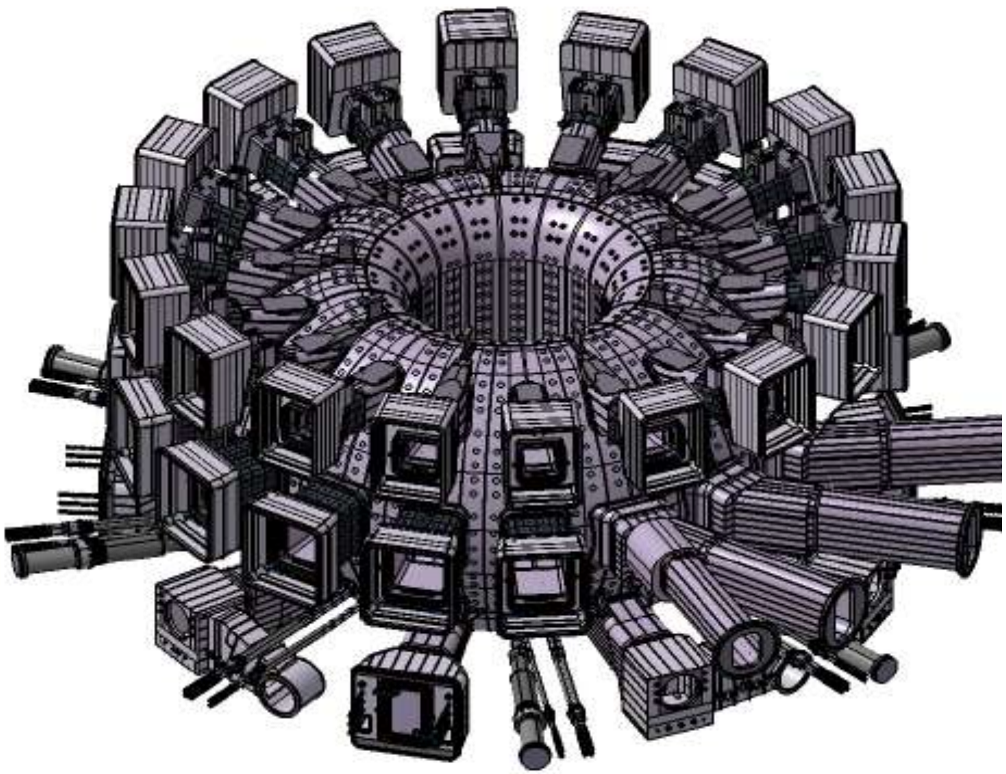
- **CS Coil Stack**
  - 6 independently powered modules
  - 12m tall x 4m diameter
  - Nb_3Sn conductor
  - 13T (peak CS field)
  - 45kA (peak CS current)
  - 1000 tonnes

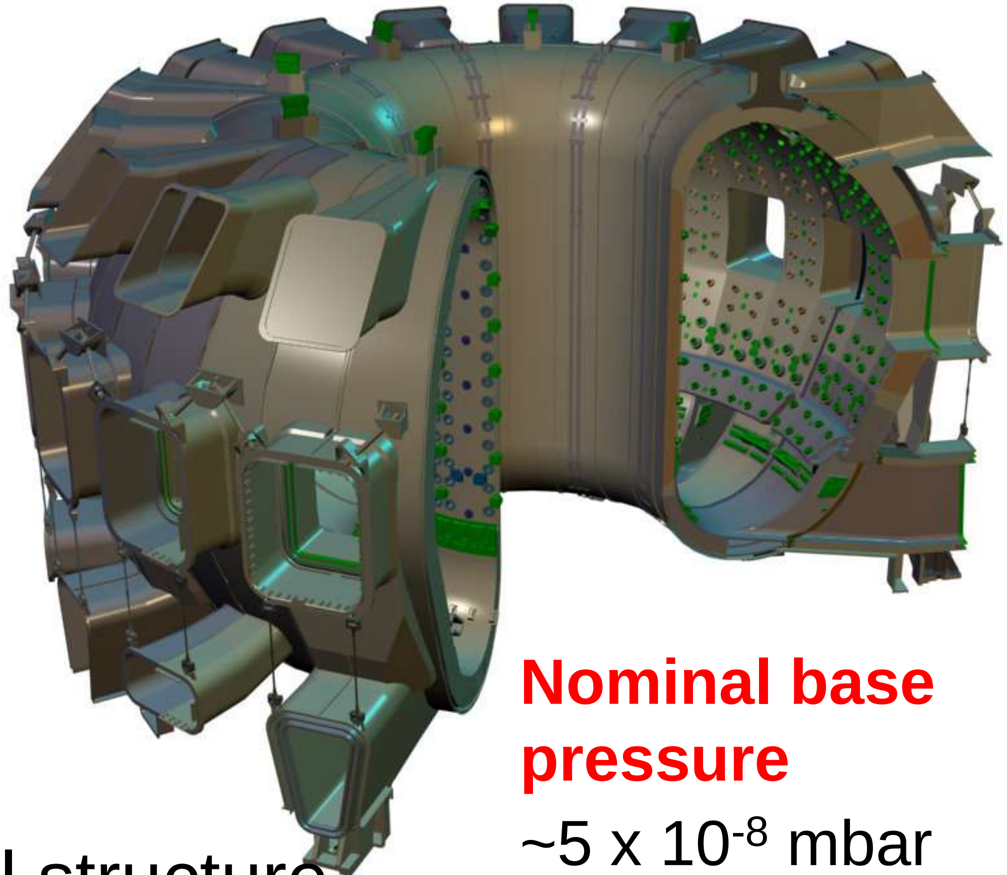
Poloidal Field Coils



- 6 PF coils
- Up to 25 m diameter
- NbTi conductor
- 6.8 T (peak PF field)
- 55 kA (peak current)
- manufactured on-site

Vacuum Vessel



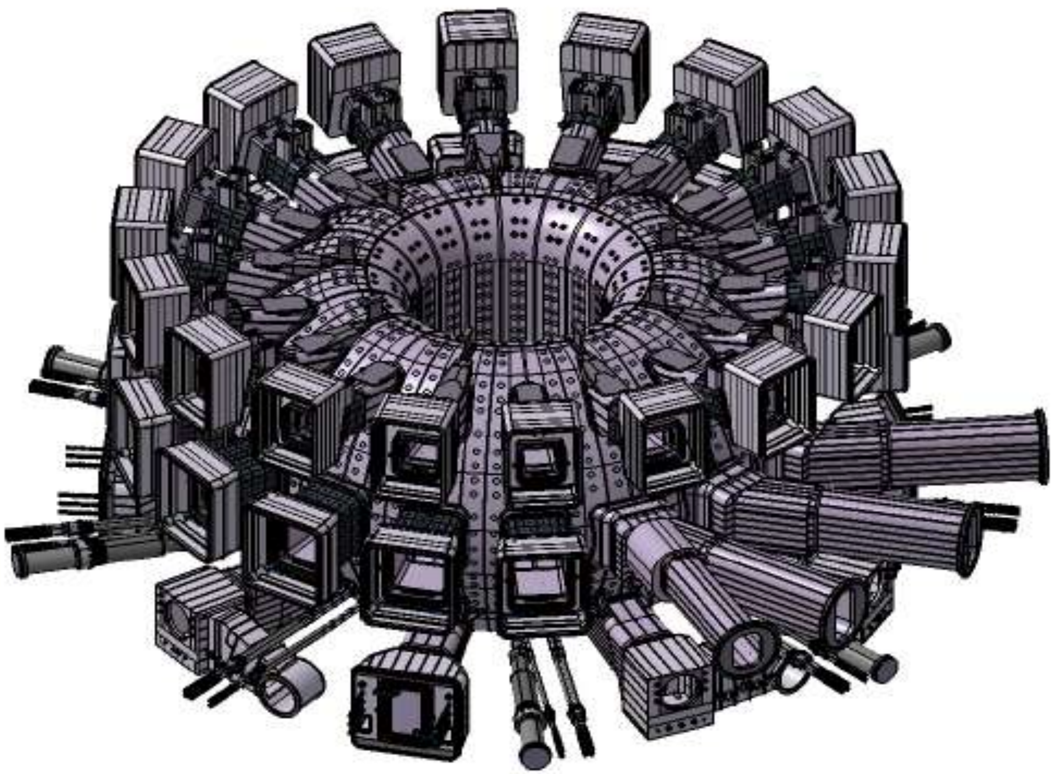


Nominal base pressure

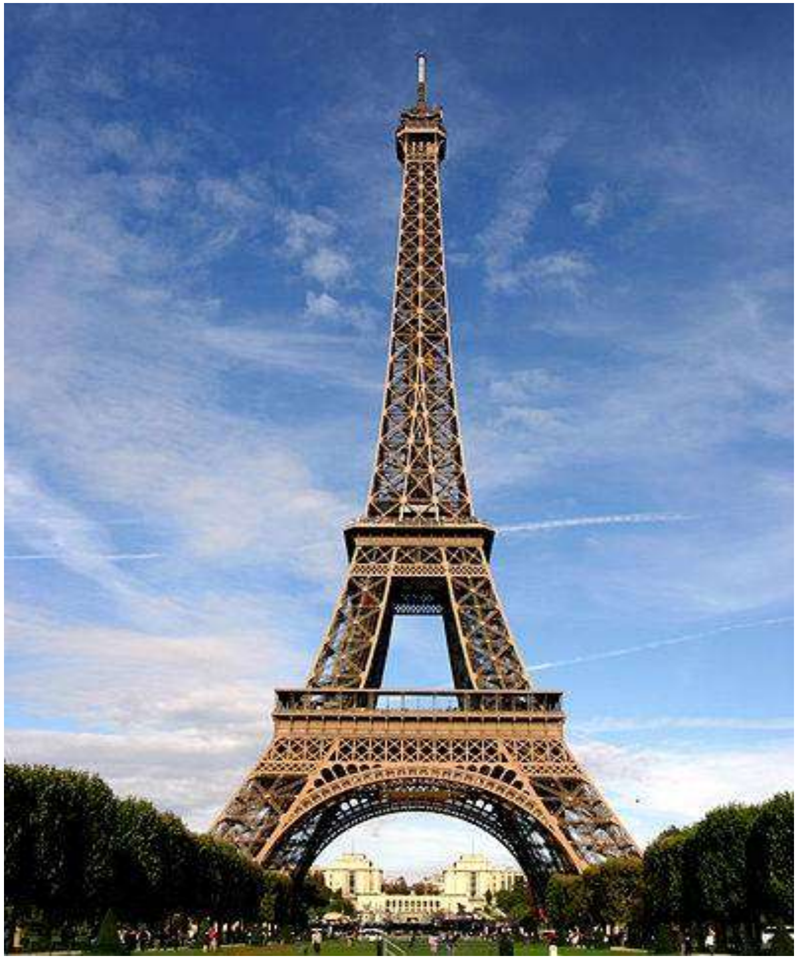
~5 x 10^{-8} mbar

- Double-walled, stainless steel structure
  - 19.4m outer diameter, 11.3m height, 5300 tonnes
  - Primary tritium containment barrier, bakeable to 200ºC
  - Must withstand enormous vertical forces during disruptions

Vacuum Vessel

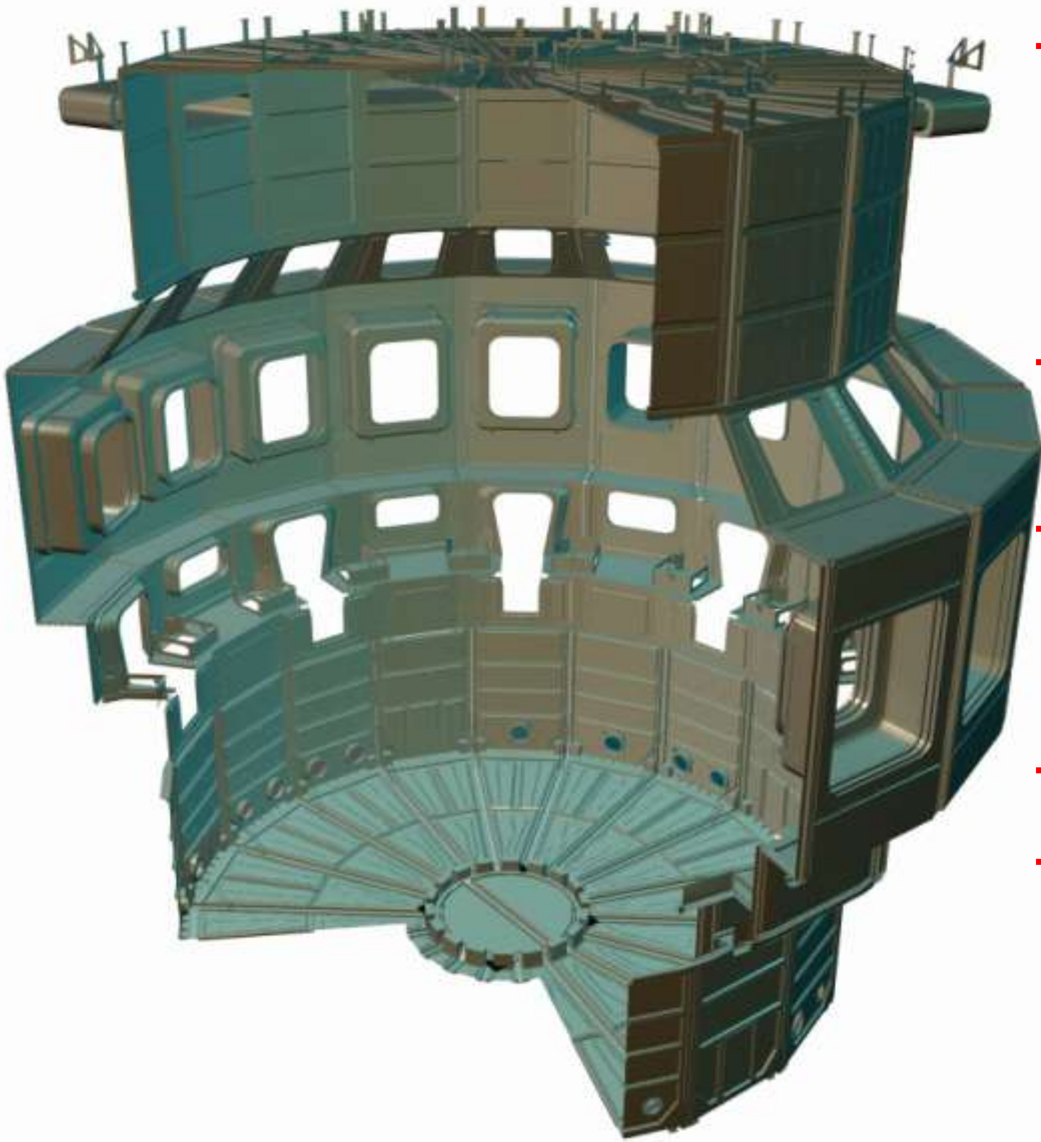


- Weighs about 25% less than the Eiffel Tower (more with in-vessel components included)



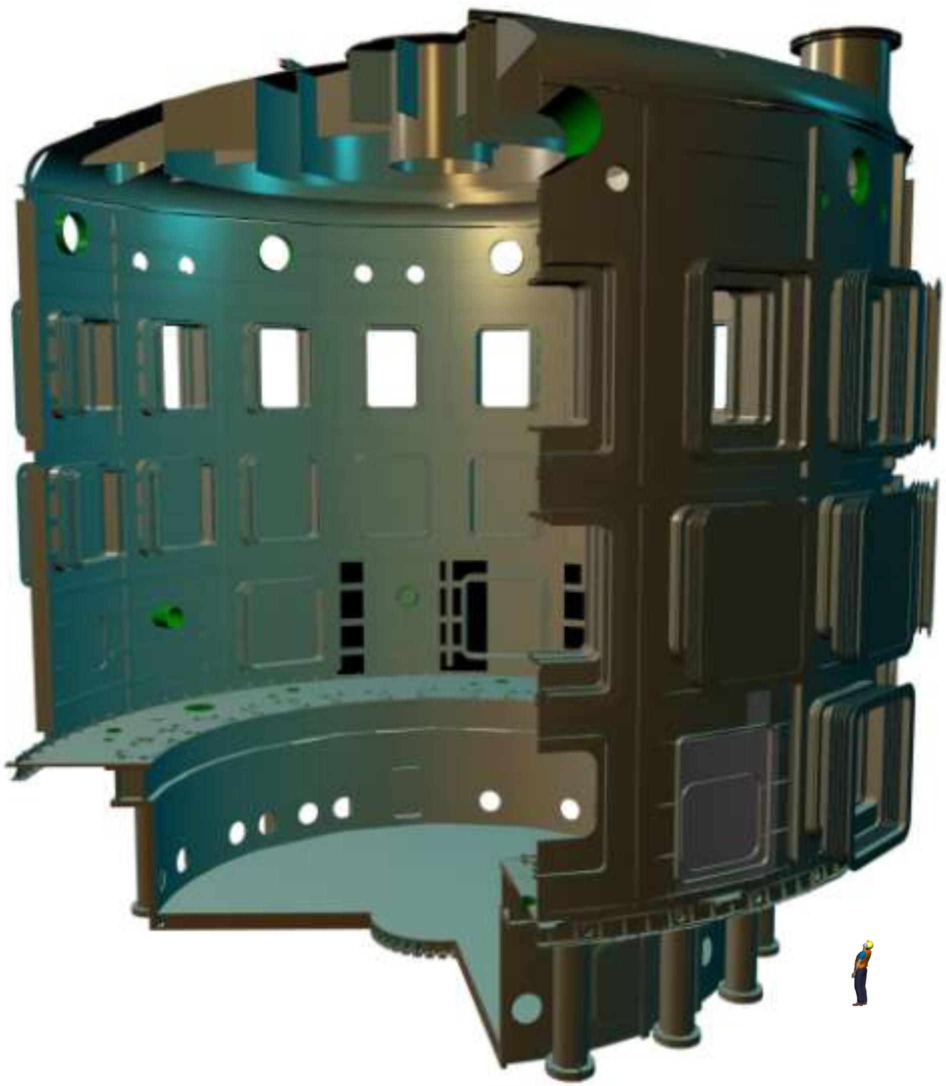
7300 tonnes
324 m tall

Main inner heat shield



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

ITER Cryostat



Outer thermal shield

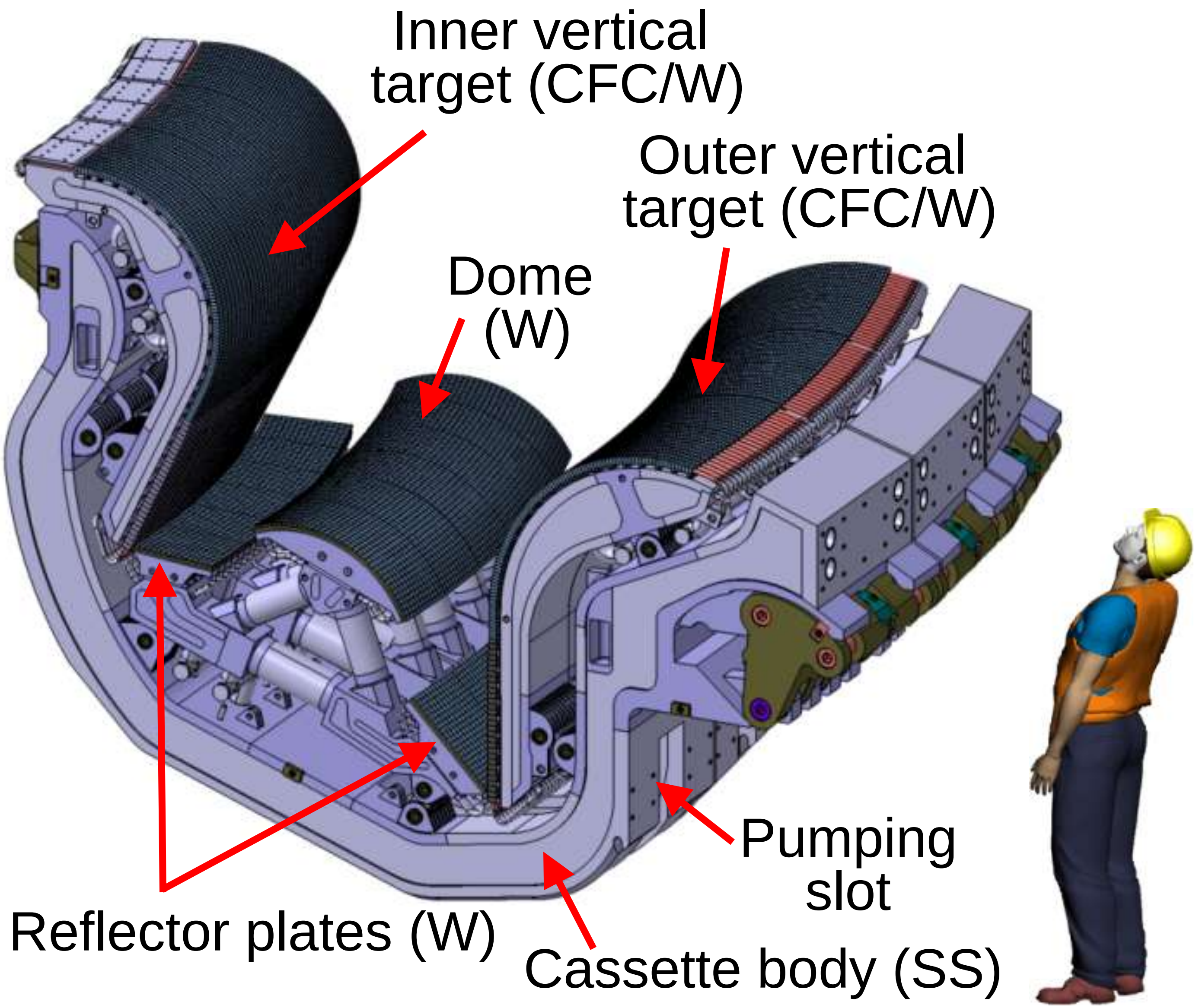
- Diameter: 29.2 m
- Height: ~29 m
- Mass: ~3300 tonnes
- Base pressure <10^{-4} mbar

Principal in-vessel components

First wall/blanket → heat exhaust, impurity management, nuclear shielding

Divertor → particle and heat exhaust

Divertor assembly



54 divertor assemblies (~8.7 tonnes each)

4320 actively cooled heat flux elements

Bakeable to 350°C

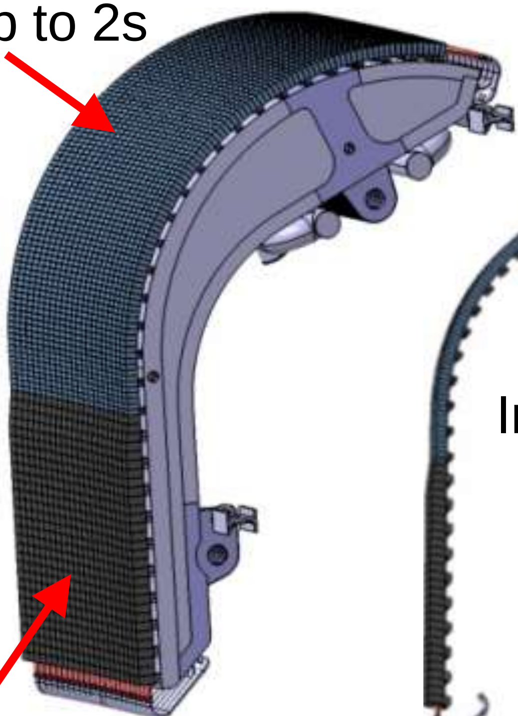
First divertor (non-active operation):

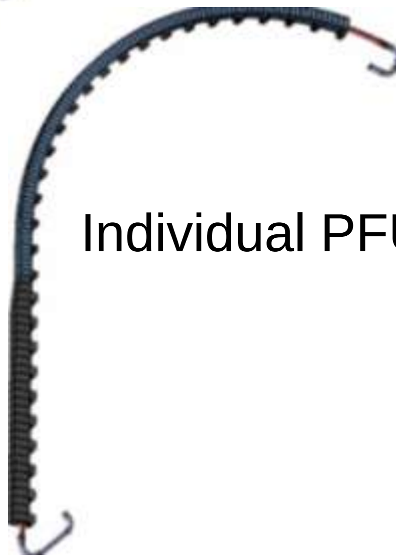
CFC at strike points
W on the baffles

All-W for nuclear phase

First divertor design power handling

BAFFLES: **W monoblocks**
5 MWm^{-2} steady state, 10 MWm^{-2}
for up to 2s

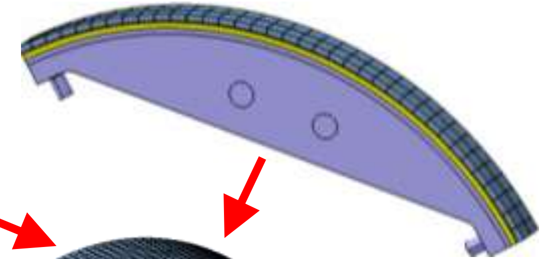


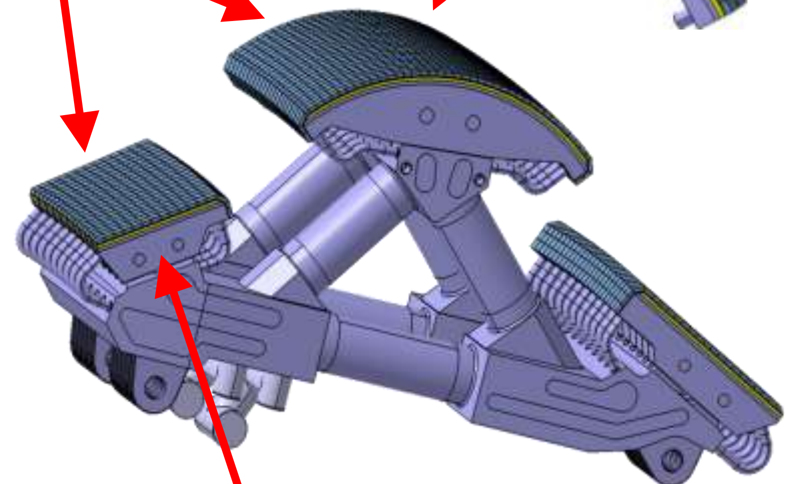


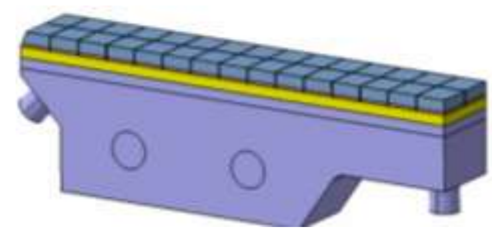
Individual PFU

DOME& REFLECTORS
W flat tiles
5 MWm^{-2} steady state
10 MWm^{-2} for 2 s

Individual PFU





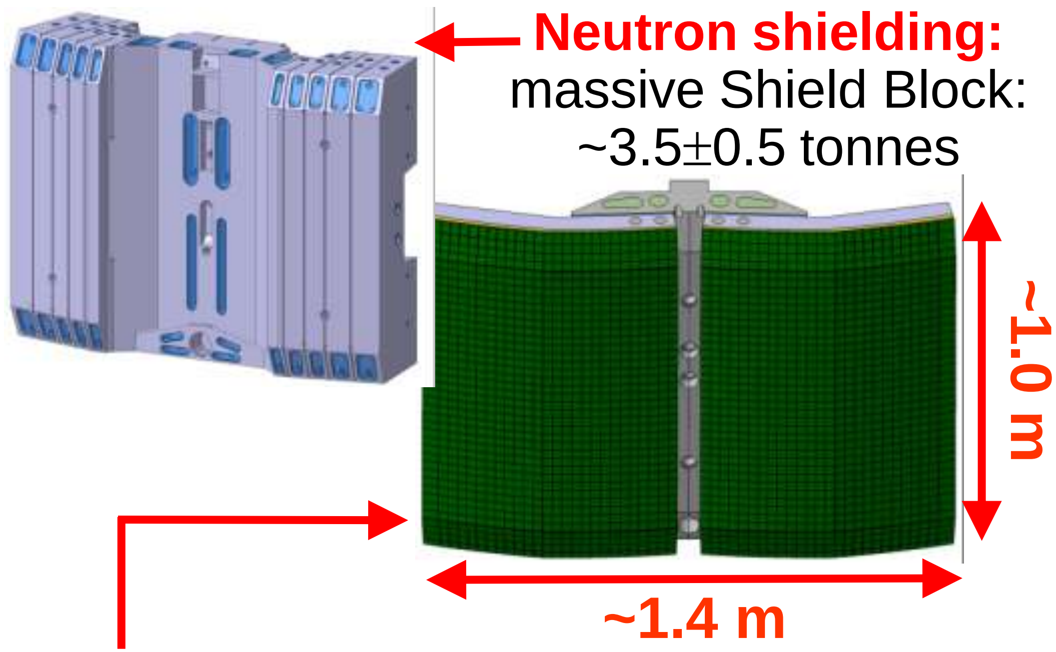


LOWER VERT. TARGETS
CFC monoblocks
10 MWm^{-2} steady state
20 MWm^{-2} for ~10 s slow transients

Individual PFU

First wall/blanket

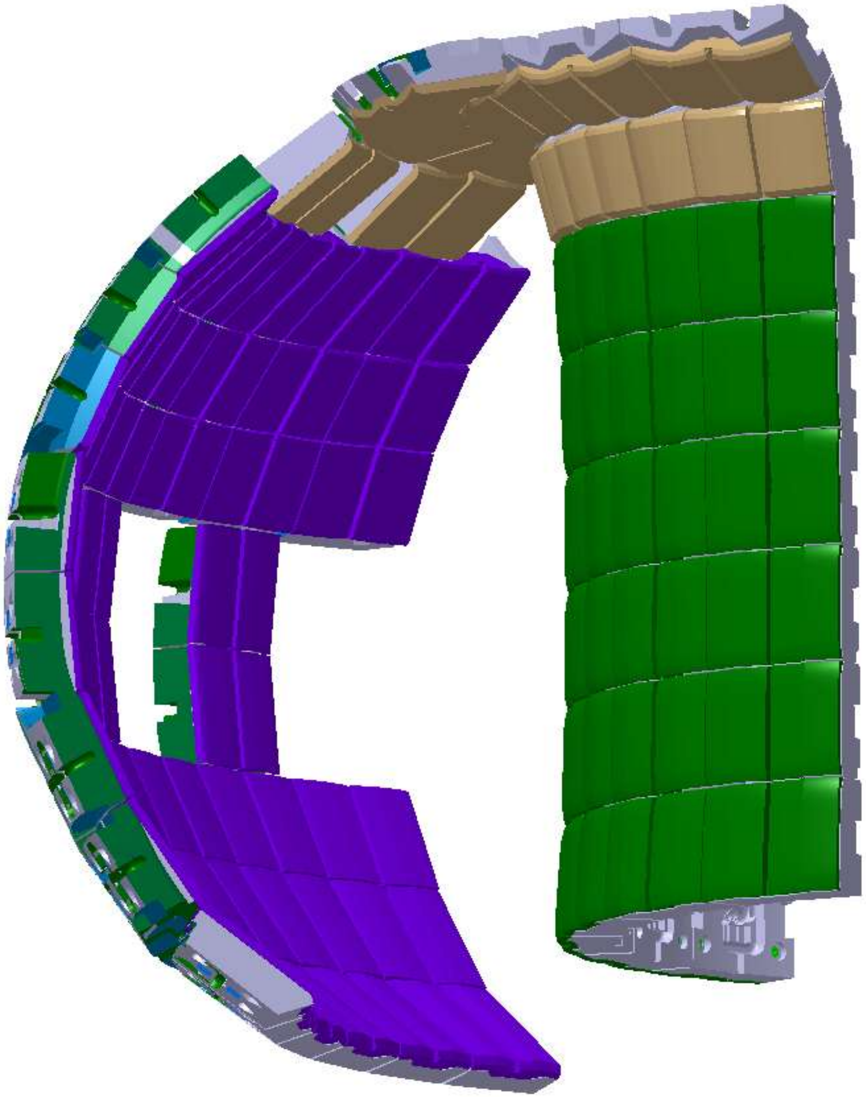
- Be-tiled first wall panels
  - Low atomic number material → minimizes fuel dilution and photonic radiation losses if impurities reach the core
  - Good oxygen getter → reduce effect of low leak rates
  - Originally thought to be a low tritium retention material → see 2nd talk



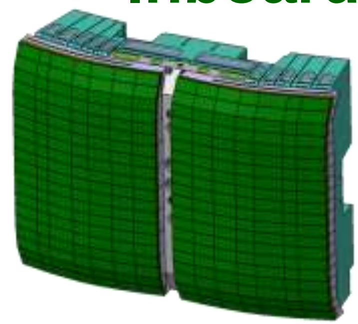
Plasma-facing surfaces: separable actively cooled with symmetric wings to shadow central access slot and protect against module-to-module misalignments

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

A generic shaping solution

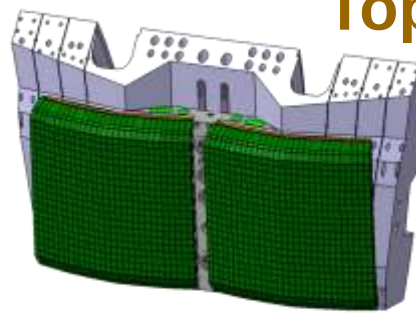


Inboard



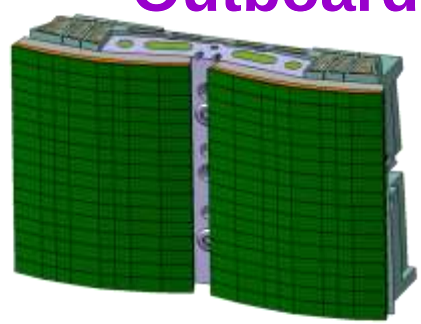
BM #1-6
Central column
HFS start-up
Toroidal & poloidal shaping

Top



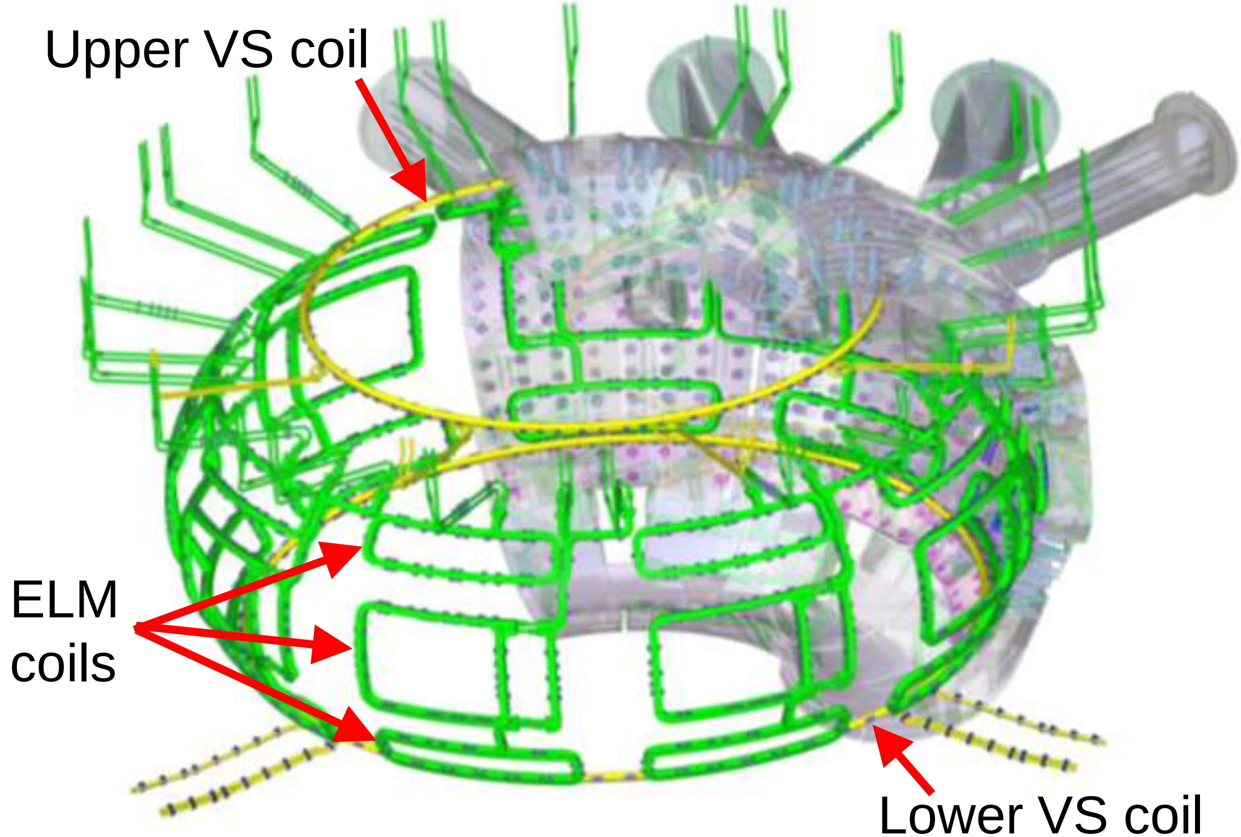
BM #7-10
Secondary divertor region
Toroidal & poloidal shaping

Outboard



BM #11-18
Outboard
LFS start-up/ramp-down
Toroidal shaping

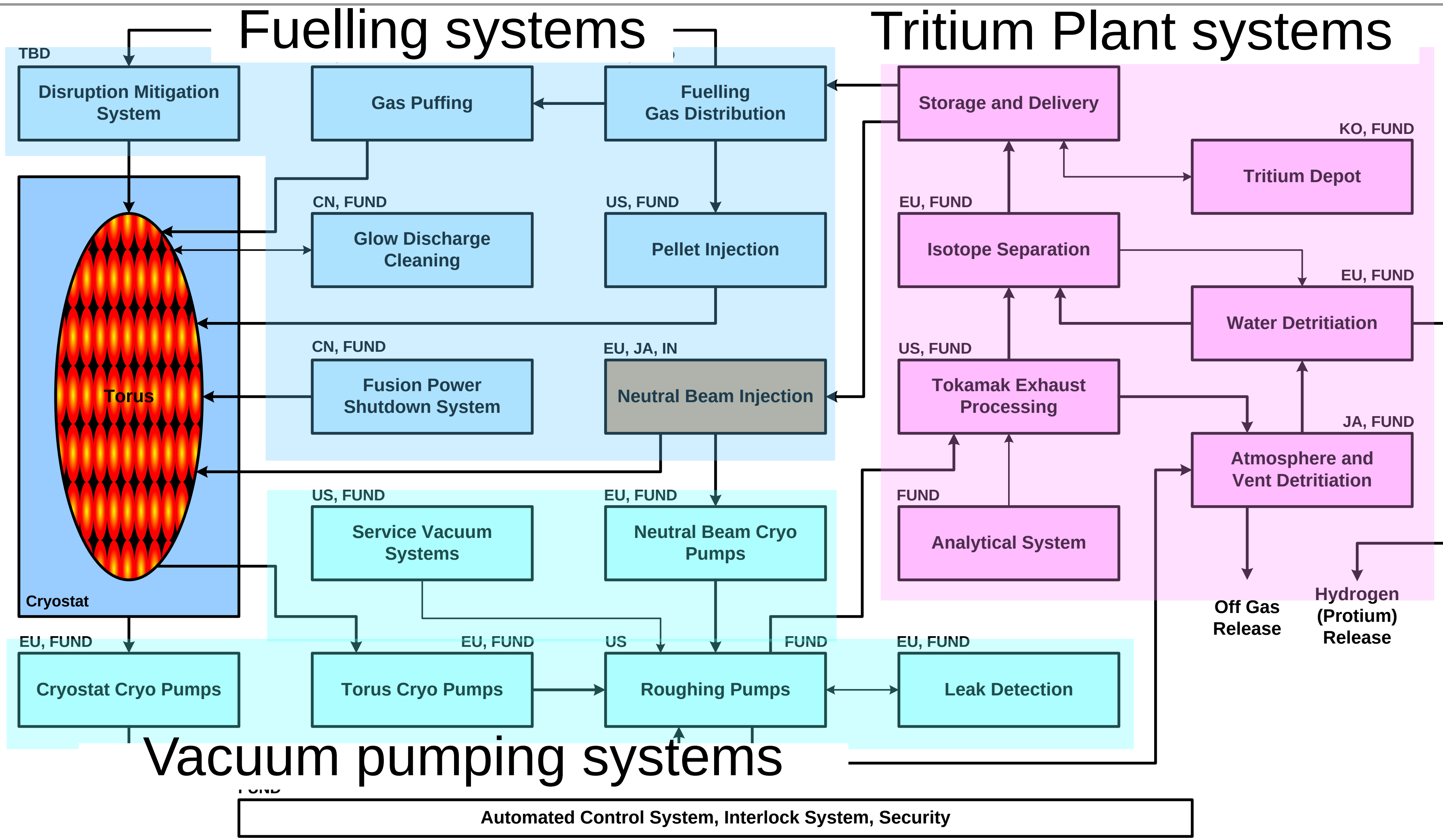
In-vessel coils



VS Coils	Normal Operation
Number	2 coils - 4 turns each
Maximum current (pulsed)	± 60 kA (240 kAt/coil)
Voltage	± 2.3 kV
Total Weight	~15 t
ELM Coils	
Number	27 coils - 6 turns each
Maximum current	± 15 kA (± 90 kAt/coil)
Voltage	± 230 V
Total Weight	~62 t

- In-vessel coils are being designed for ELM mitigation and/or suppression, resistive wall mode and vertical stabilisation
  - 9 toroidal x 3 poloidal array on (outboard) internal vessel wall (ELMs, RWM)
  - Upper/ lower loops for vertical stabilisation

The fuel cycle



Tritium Plant

- Uses techniques typical of gas processing, but on a large scale
  - H_2, D_2, T_2 gaseous under normal conditions → colourless, odourless and tasteless
  - ITER core fuelling will have to be performed by injection of solid ice pellets of D and T → melting points of D_2, T_2 are 18.7K (-254.4°C) and 20.6K (-252.5°C), respectively
  - Tritium Plant Isotope Separation Systems distills liquid hydrogen
- All pumps, pipe work, valves, instruments must be tritium compatible
  - Leak tight to highest standards (individual leak rates < 10^{-10} $Pa m^3 s^{-1}$)
  - Only metals or ceramics in direct contact with tritium → organic materials (polymers, etc.) degrade due to beta radiation
  - Tritiated water to be avoided at all costs (highly corrosive)
- 4kg of tritium will be held on ITER site → only about 20 kg of tritium anywhere in the world at any one time!

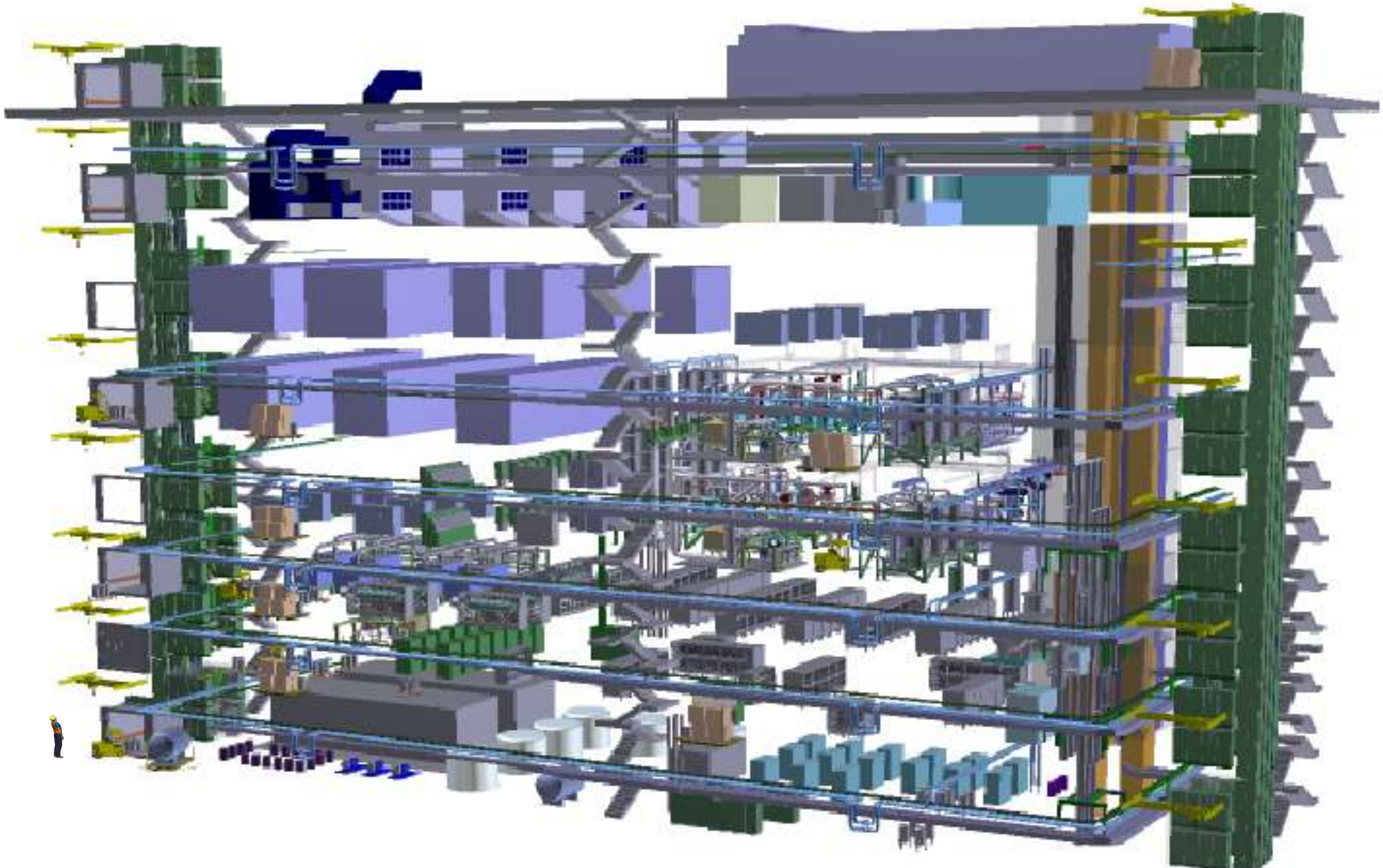
Tritium Plant

7 storeys
(2 below ground level)

L = 80 m

W = 25 m

H = 35 m

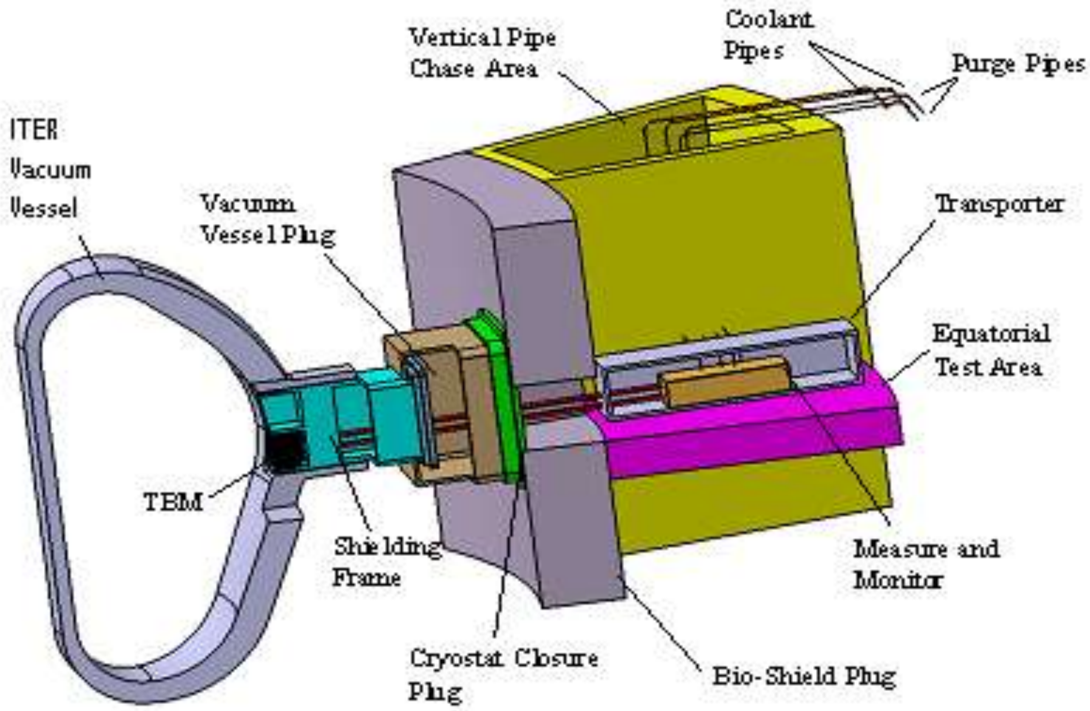


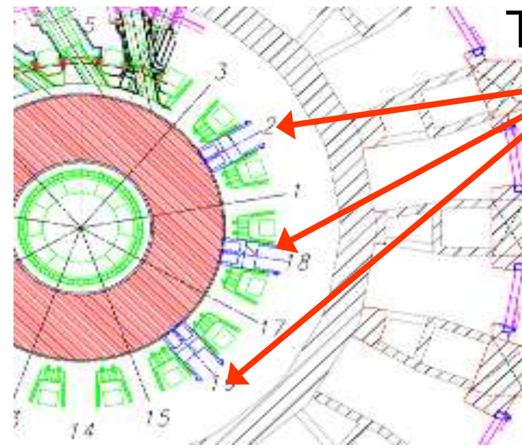
- A 400 s ITER burning plasma will require ~50 g of tritium fuel, but only ~0.3% will be burned by fusion reactions → T reprocessing mandatory

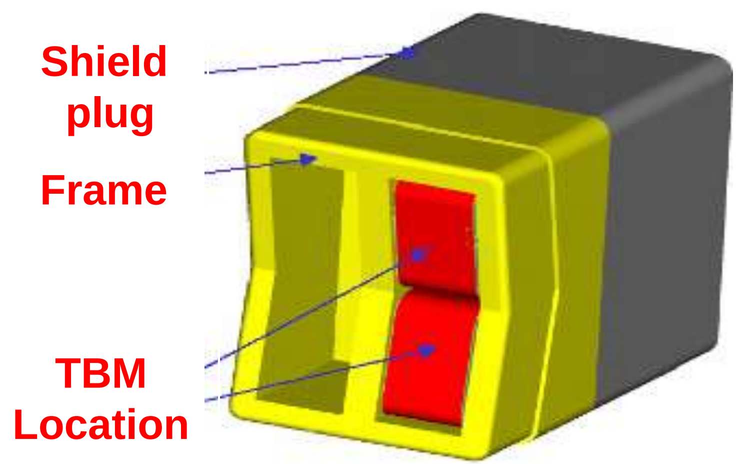
Test Blanket Modules - Tritium Breeding

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

$n + {}^{7}Li \rightarrow T + {}^{4}He + n - 2.47\ MeV$





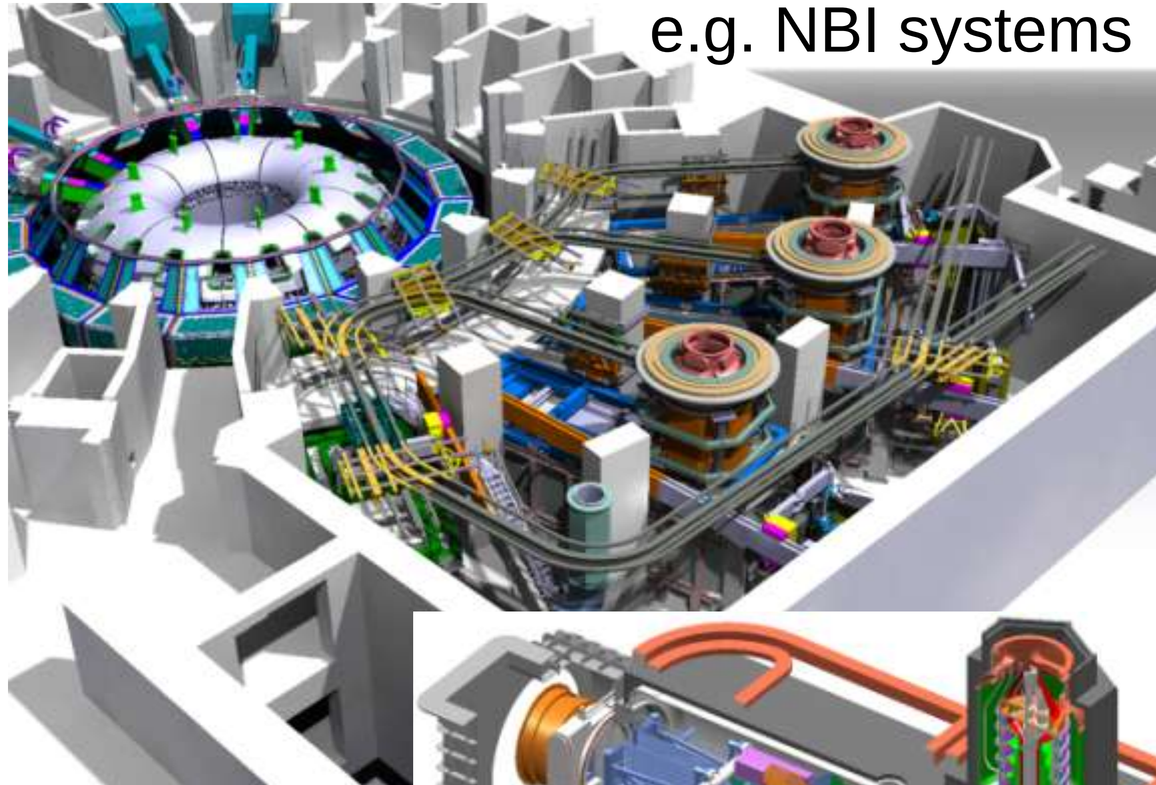


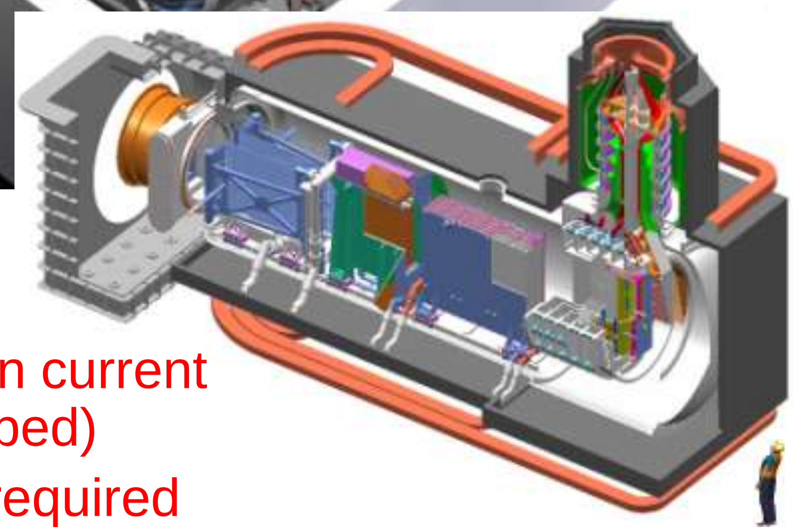
- Three dedicated stations for testing up to six tritium breeding concepts

Heating the Plasma

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

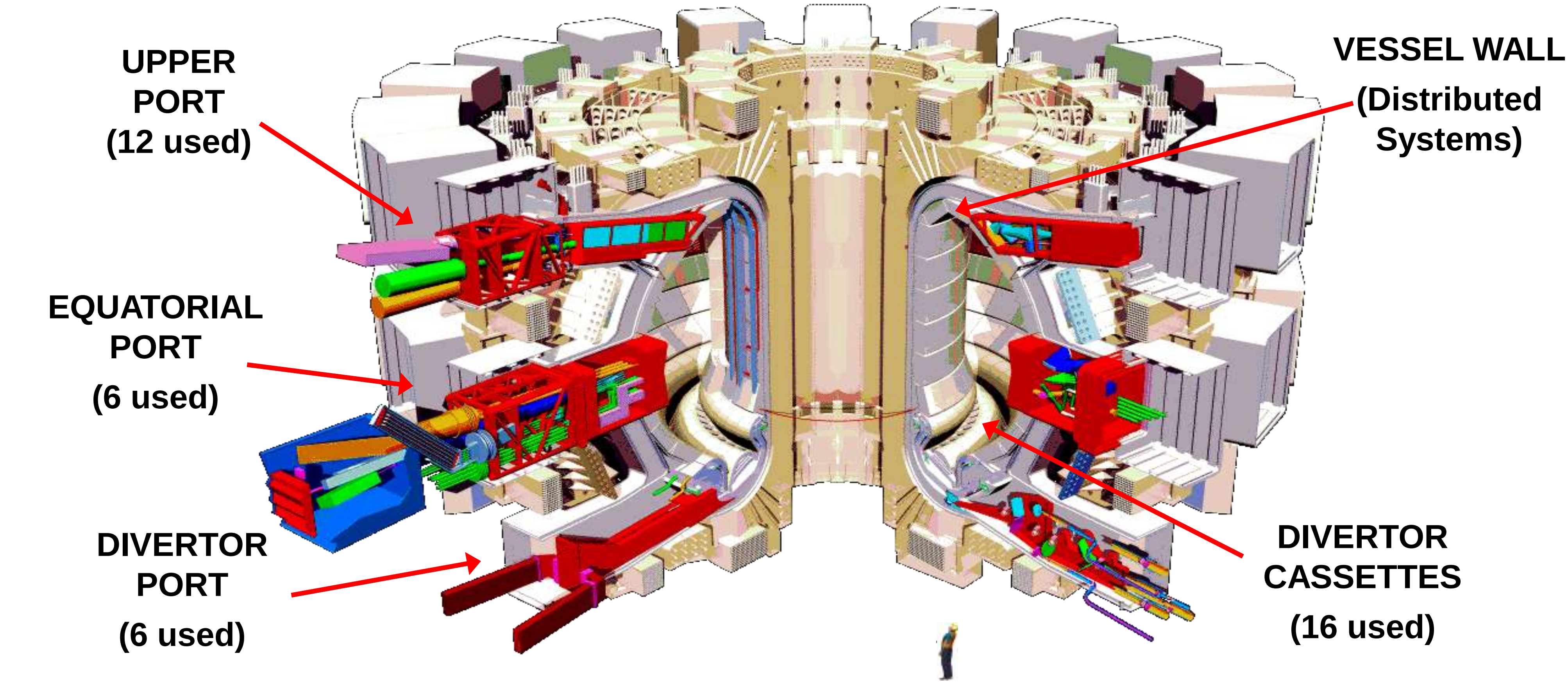
P_{aux} for Q_{DT} = 10 nominal scenario: 40 – 50 MW





- All are on an unprecedented scale
  - Upscale from known technologies, operating on current tokamaks (-ve ion NBI source less well developed)
  - Systems have flexibility for power upgrades if required

Analyzing the Plasma - ITER Diagnostics



- About 40 major diagnostic systems eventually
  - Required for protection, control and physics studies
  - Will be a superbly diagnosed tokamak when all foreseen systems installed
  - Significant challenges in a nuclear environment compared to present devices

Some key operational challenges

(can only scratch the surface here in such a short lecture → ITER will face many challenges during operation and this is why it needs to be built!)

ITER Scenarios

Baseline scenarios

Single confinement barrier

- ELMing H-mode
  - Q = 10 for ≥ 300 s
  - Well understood physics for extrapolation (control, self-heating, α-particle physics, plasma-facing component power handling)
  - Physics-technology integration
- Hybrid
  - Q > 5 for 100 – 1000 s
  - Conservative scenario for technology testing
  - Performance projection based on ELMy H-mode
  - Lower current (12-14 MA) with higher non-inductive current drive

Advanced scenarios

Multiple confinement barriers

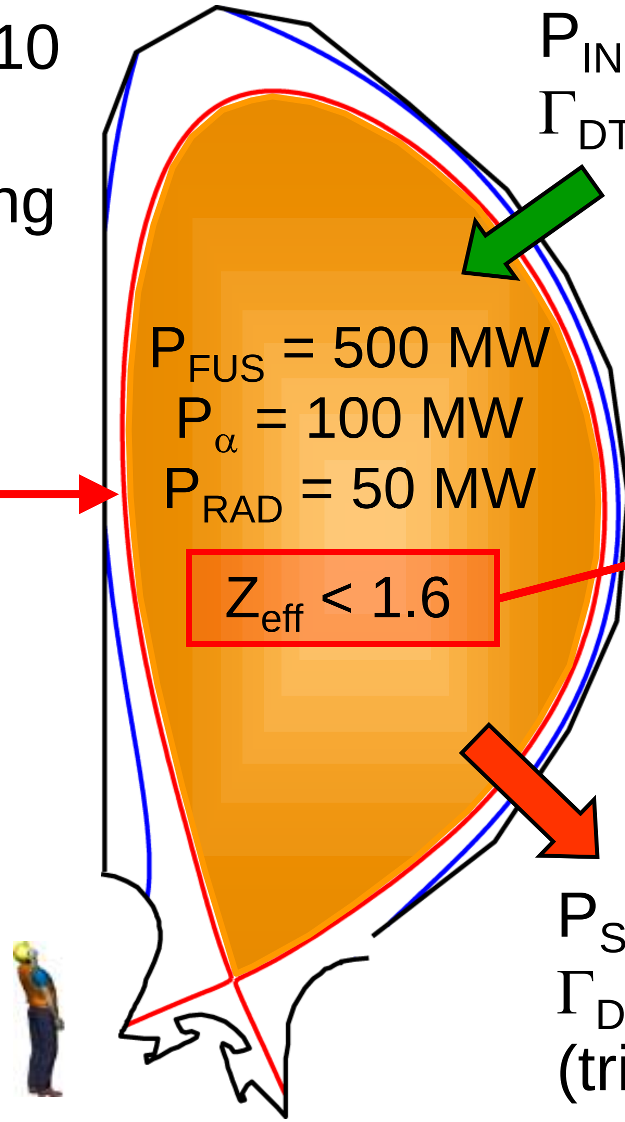
- Satisfy steady state objectives
- Prepare DEMO
- But not as well developed as the baseline → issues of
  - Controllability
  - MHD stability
  - Divertor/impurity compatibility
  - Extrapolation of regime to ITER
  - α-particle confinement

Steady state exhaust

ITER $Q_{DT} = 10$
t ~ 400 s
Type I ELMing
H-mode

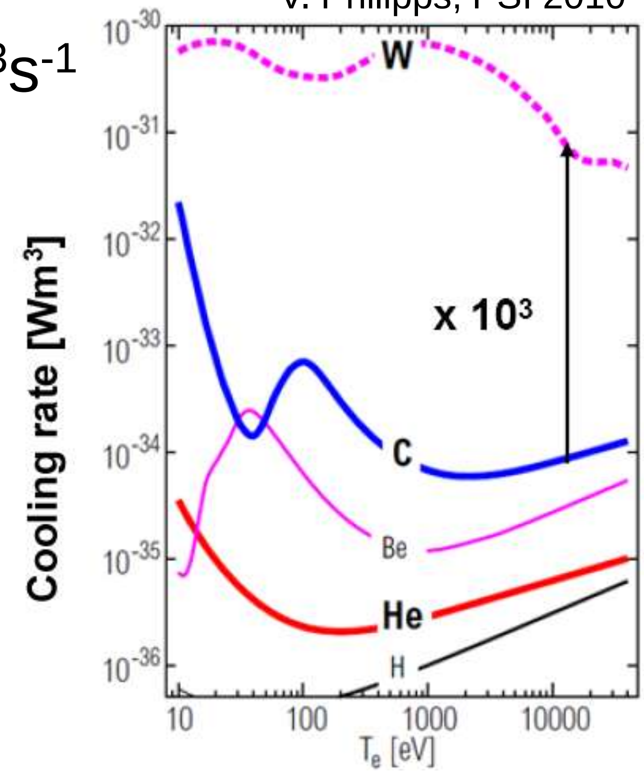
Reference
magnetic
equilibrium

$P_{IN} = 50$ MW
$\Gamma_{DT,IN} \sim 100$ Pam^{3}s^{-1}



Challenging for high Z PFCs

V. Philipps, PSI 2010

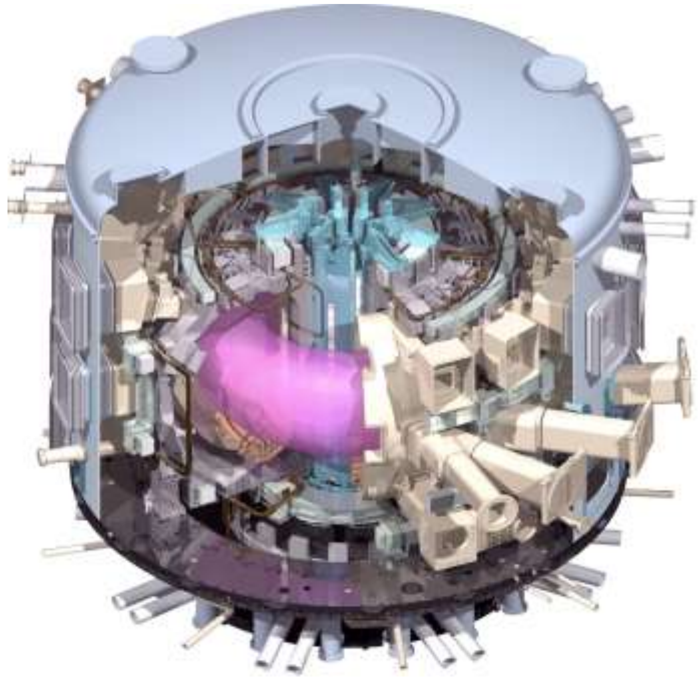


$P_{SOL} \sim 100$ MW
$\Gamma_{DT,OUT} \sim 99.5$ Pam^{3}s^{-1}
(triton burn-up only ~0.5%)

Plasma control on ITER

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

Measurements:
~80 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

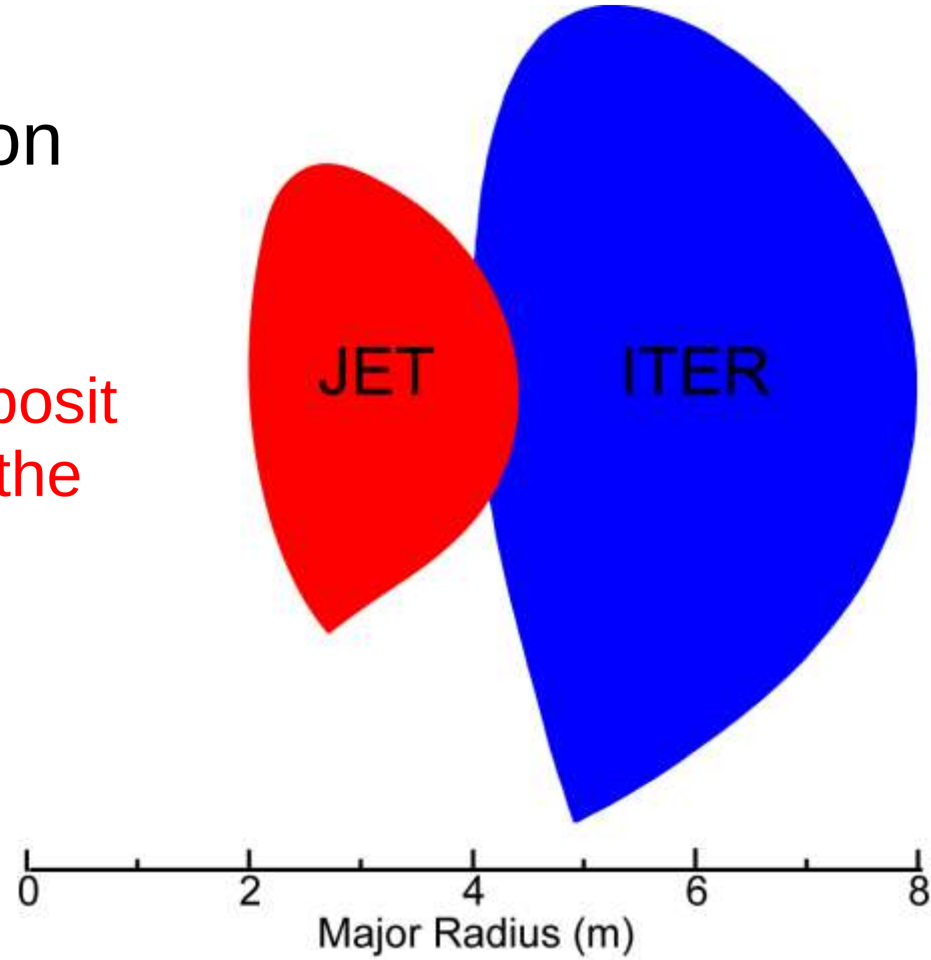
Plasma transients

ITER will be the first tokamak in which plasma-facing components will play a major role in machine performance and availability → ITER must demonstrate that sustained fusion performance can be compatible with materials facing the plasma

BUT ....

Upscale to ITER is a big step

- Plasma stored energy ~ $\propto R^5$
- But area for energy deposition on plasma wetted areas $\propto R\lambda_q$
  - W_{plasma}(ITER) ~ 35W_{plasma}(JET) → during transients, ITER will deposit 35x as much energy on only ~2x the surface area
  - Surface temperature rise due to transient: $\Delta T \propto E_{trans}/(A_{wet}t^{1/2})$
  - E_{trans}: 1 – 350 MJ, t: 0.5 – 5 ms, A_{wet} ~ few m^2 → energy densities easily several MJm^{-2}



Umitigated ITER transients (ELM and disruption loads) will easily drive severe melting of metallic surfaces → lifetime issues

Plasma transients – biggest threat to ITER

Disruptions & VDEs

Worst case full energy disruptions → peak energy densities on the divertor of 5.0-20 MJm^{-2} on timescales of 1.5-3 ms (thermal quench)

Current quench: runaway electron currents up to 12 MA with 10-20 MeV in localised areas on timescales of a few 10's of ms

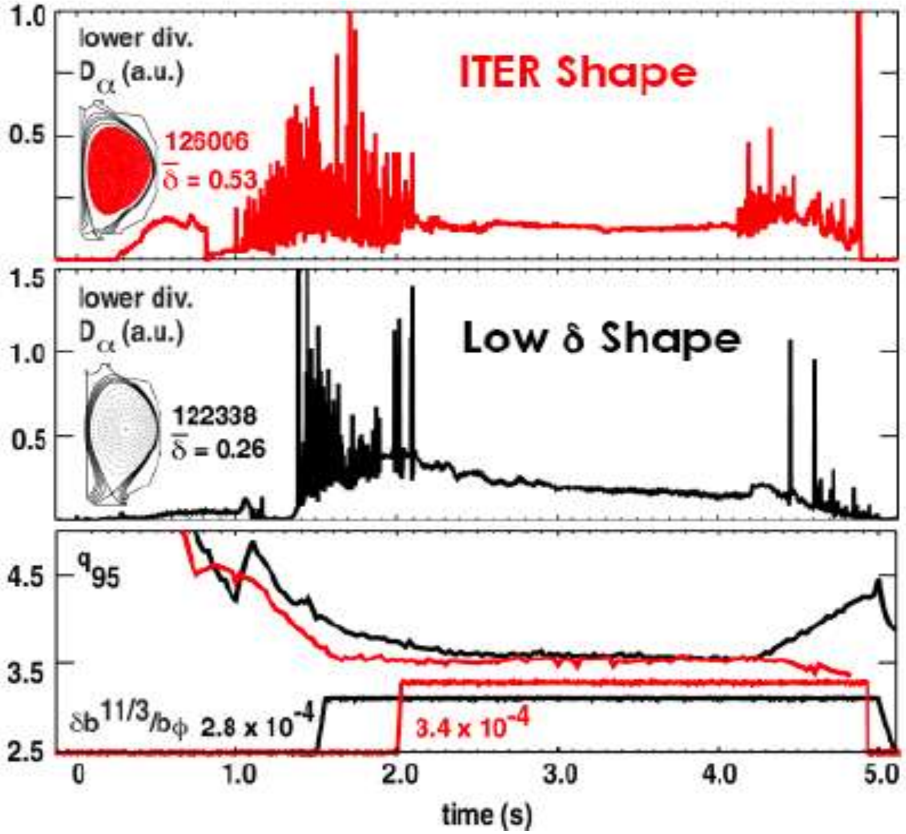
ELMs

"Natural" ELMs expected to expel ~6% of W_{plasma} at 1-2 Hz → peak energy densities on ITER divertor of 2-10 MJm^{-2} on timescales of 250-500 μs

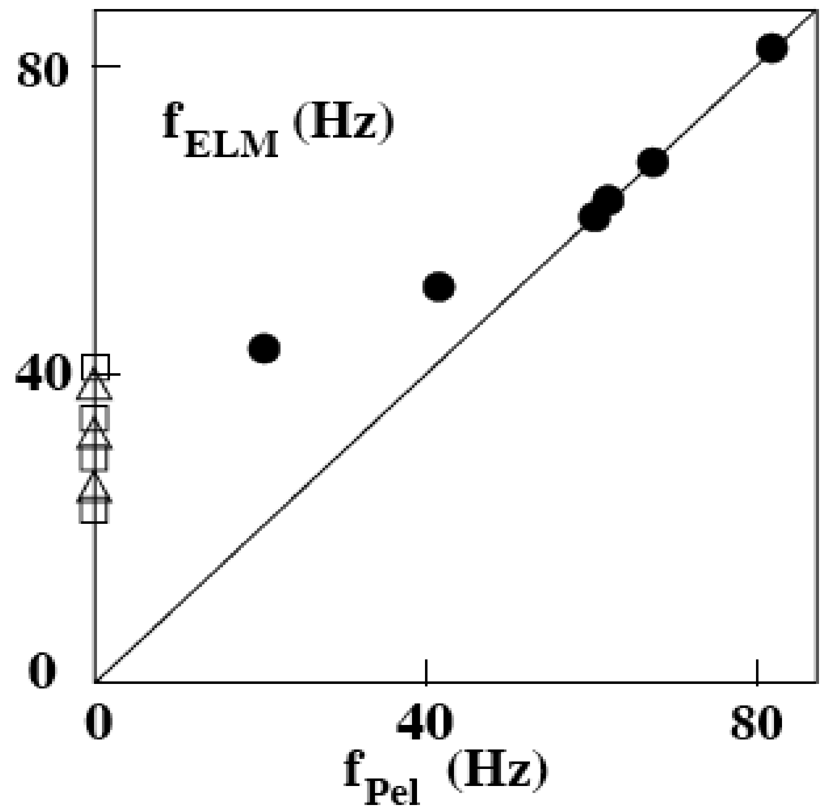
No material can tolerate these energy densities → reliable ELM and disruption avoidance and mitigation mandatory

We have some hope for ELM mitigation

Magnetic control on DIII-D



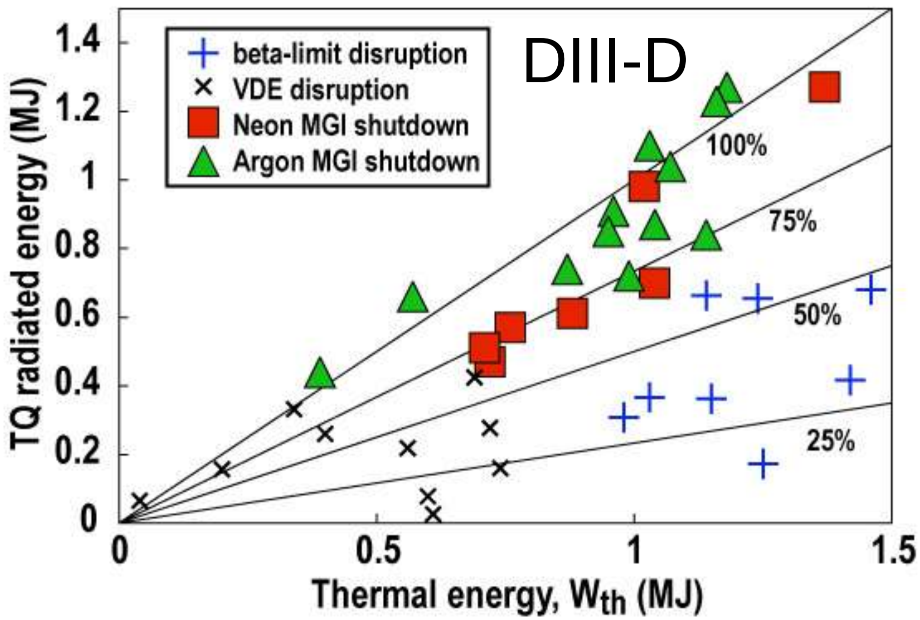
Pellet pace-making on AUG

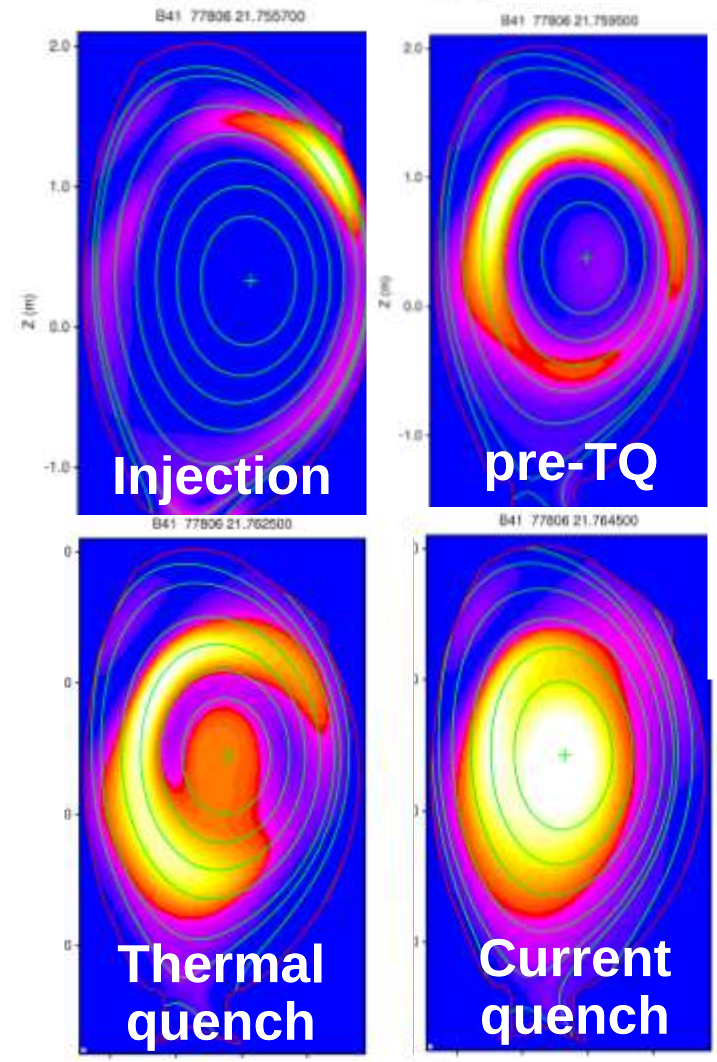


- Provisions for both systems on ITER being made
  - R&D programme in the tokamak community critical in the years to first plasma
  - We need as many alternative methods in our toolbox as we can find

Also promising for disruptions

Massive gas injection to radiate plasma stored energy





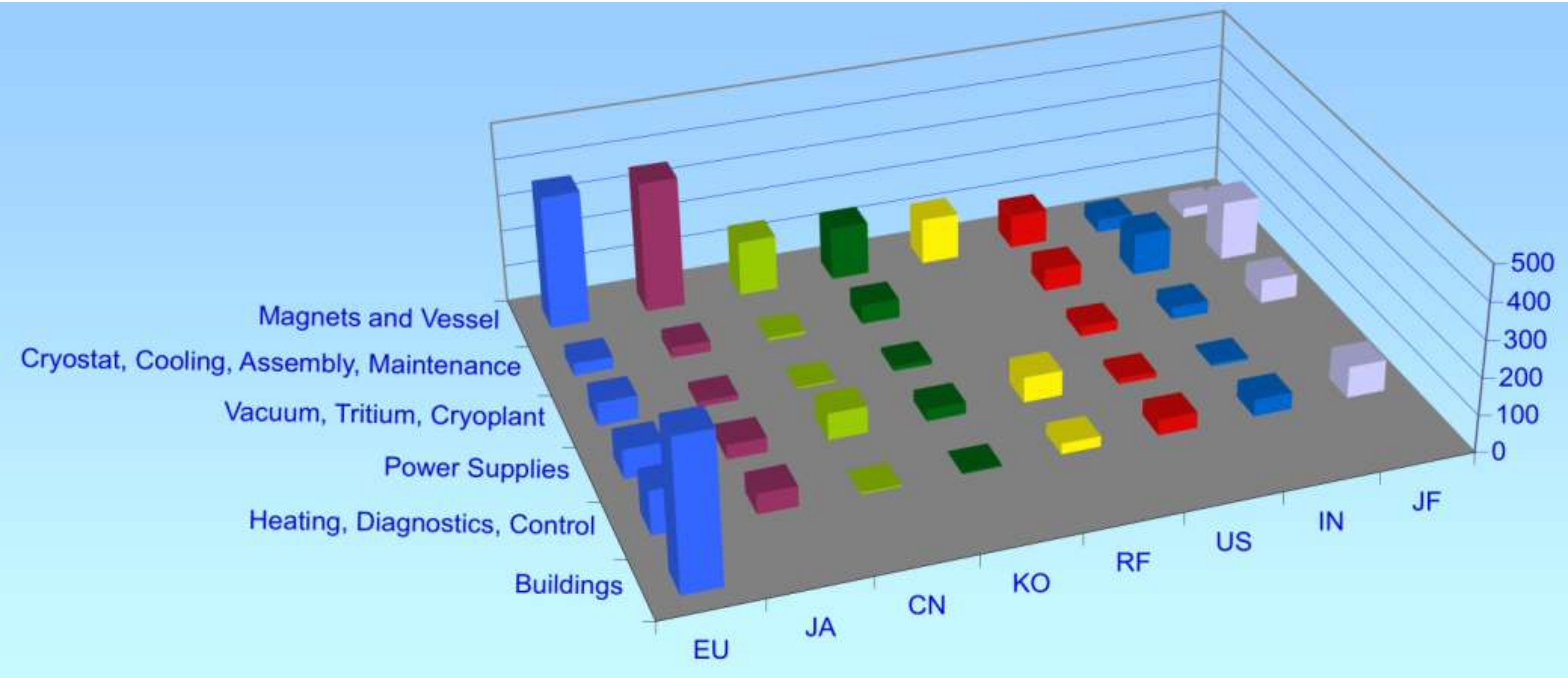
JET 10% D_2 90% Ar

- Hardware challenge to get injectors close to the fusion plasma
  - Reservoirs at 10's of bar, injecting ~0.5 kg particles in a few ms!
  - Careful not to switch problem elsewhere → MGI can shorten current quench times and amplify eddy current forces

Procurement and Schedule

Procurement in kind

One unique feature of ITER is that almost all of the plant components will be provided to the ITER Organization through in-kind contributions from the 7 Members



Procurement Arrangements

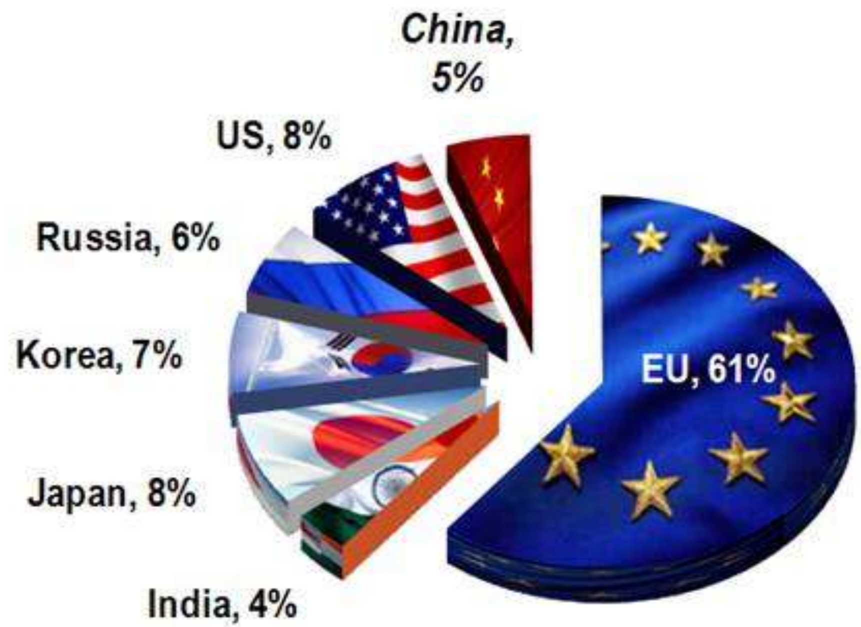
As of today, there are a total of 47 signed PAs, amounting to 1768.7 kIUA (approximately €2.65 billion), about 60% of the total in-kind PA value

About 40 PAs are scheduled to be signed by the end of 2011 for a total of ~670 kIUA (about €1 billion)

Personnel

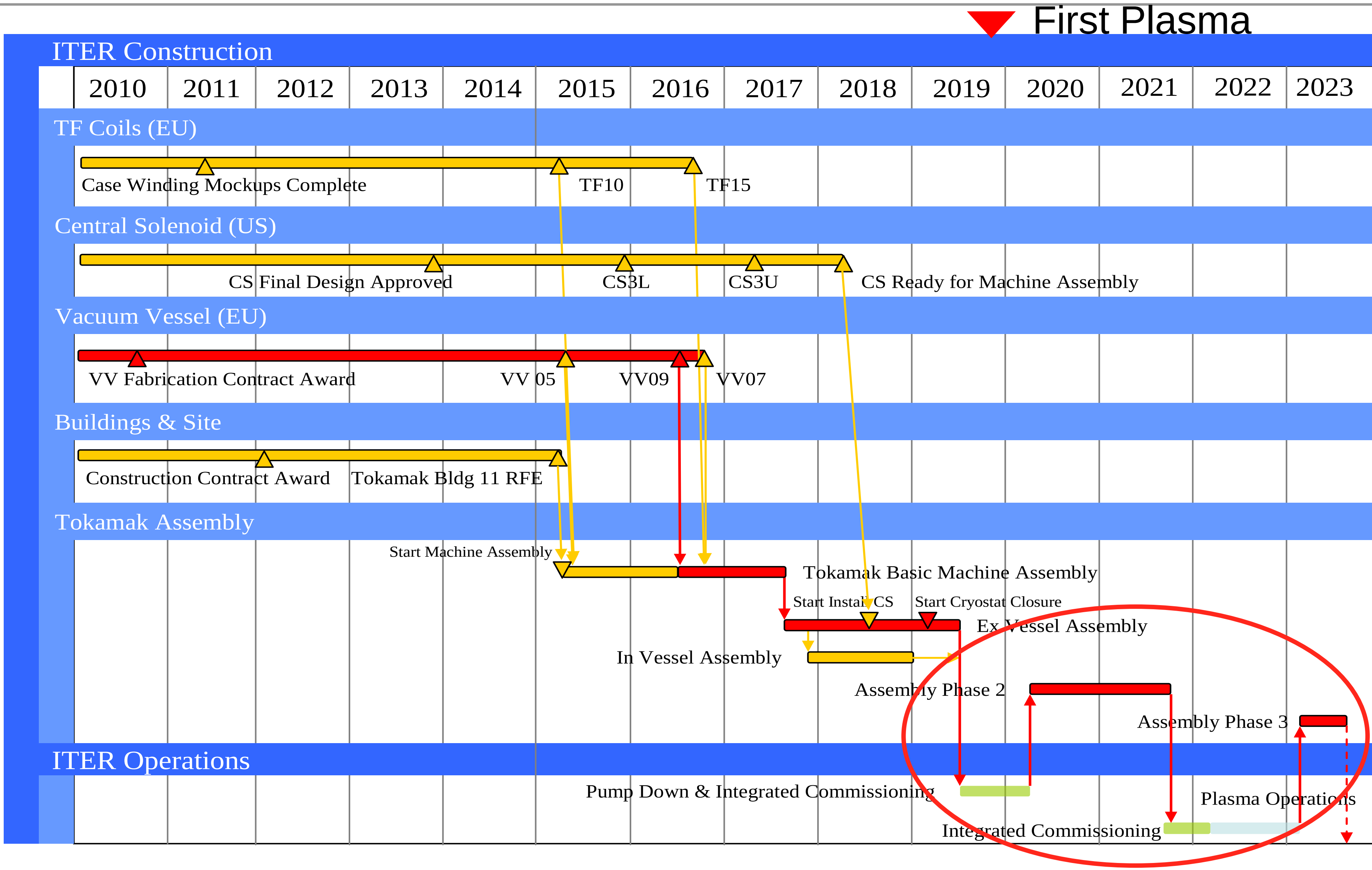
As of end 2010, the ITER Organization had a total of 69 staff members, comprising of 301 professional and 168 technical support staff members.

	Professional staff	Support staff	Total
CN	16	4	20
EU	182	125	308
IN	12	16	28
JA	25	7	32
KO	22	5	27
RU	19	3	22
US	24	8	32
Total	301	168	469

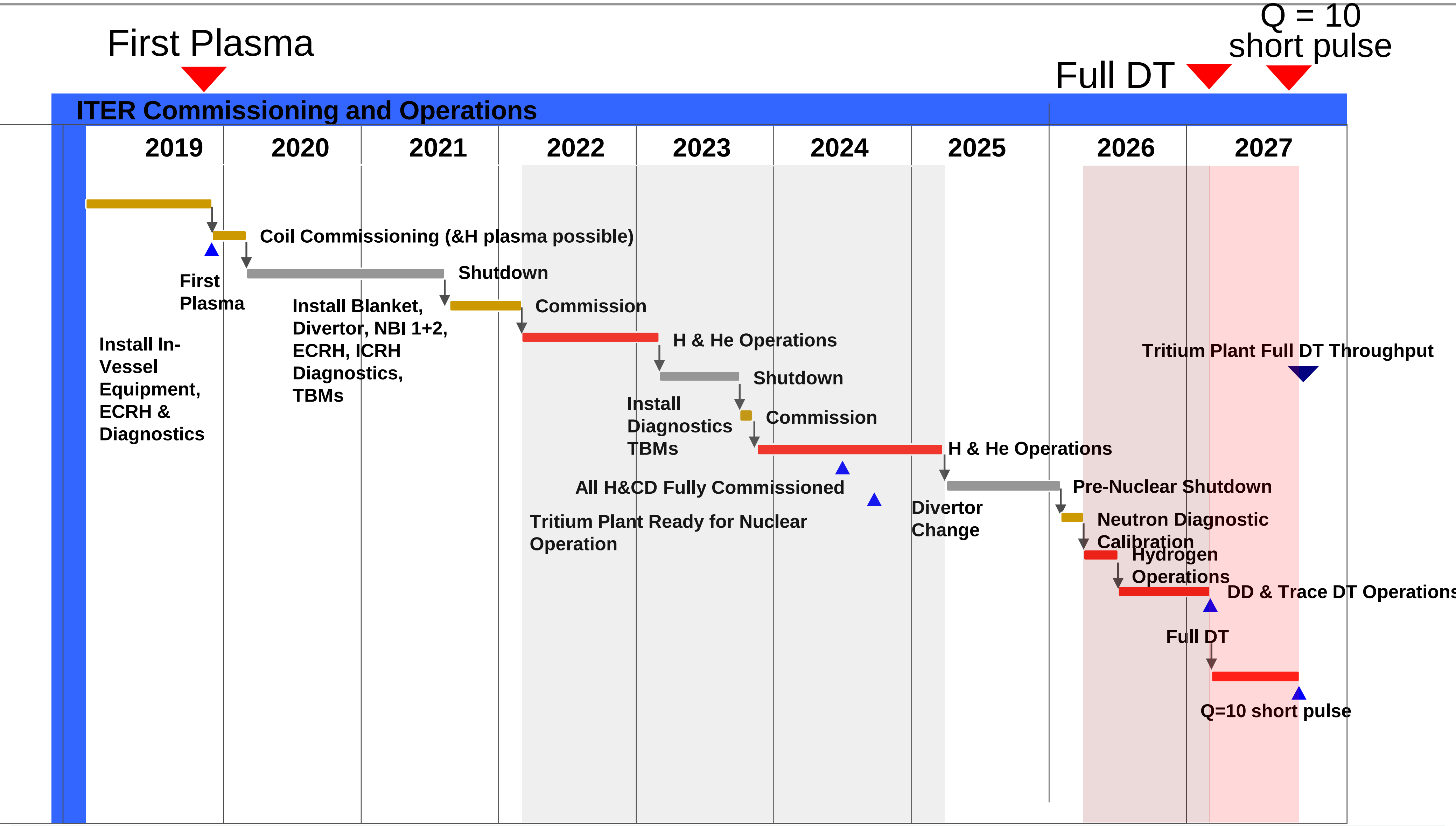


Distribution of P staff by ITER members

ITER Construction schedule



Experimental schedule to DT



Where do you fit in?

- Construction phase
  - Best way to support ITER is through the Members facilities → PhD, postdocs, R&D
  - Only a handful of physicists on the ITER team
  - Staff cannot increase much more before end of construction
  - 5 “Monaco fellows” (postdocs) every 2 years
  - Expect collaborative efforts with Members academic institutes (e.g. Masters, Phd) → is being developed slowly (political and bureacratic issues)

Where do you fit in?

- Exploitation phase
  - ITER becomes the focus of worldwide magnetic confinement research
  - The machine will be run for the Members by the central team
  - Will require a very large team of physicists/engineers familiar with tokamaks/fusion technology

Final words

- 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
- Construction underway at Cadarache funded by an international partnership of the world’s major economic and research communities
- Big progress since the team was formed to revise the Technical Baseline, to develop an overall Project Baseline, and to prepare for on-site construction of the facility!
- First plasma planned for 2019-2020

ITER is a burning plasma experiment, a major technology R&D programme and a ground-breaking international collaboration