ITER
Status and Future

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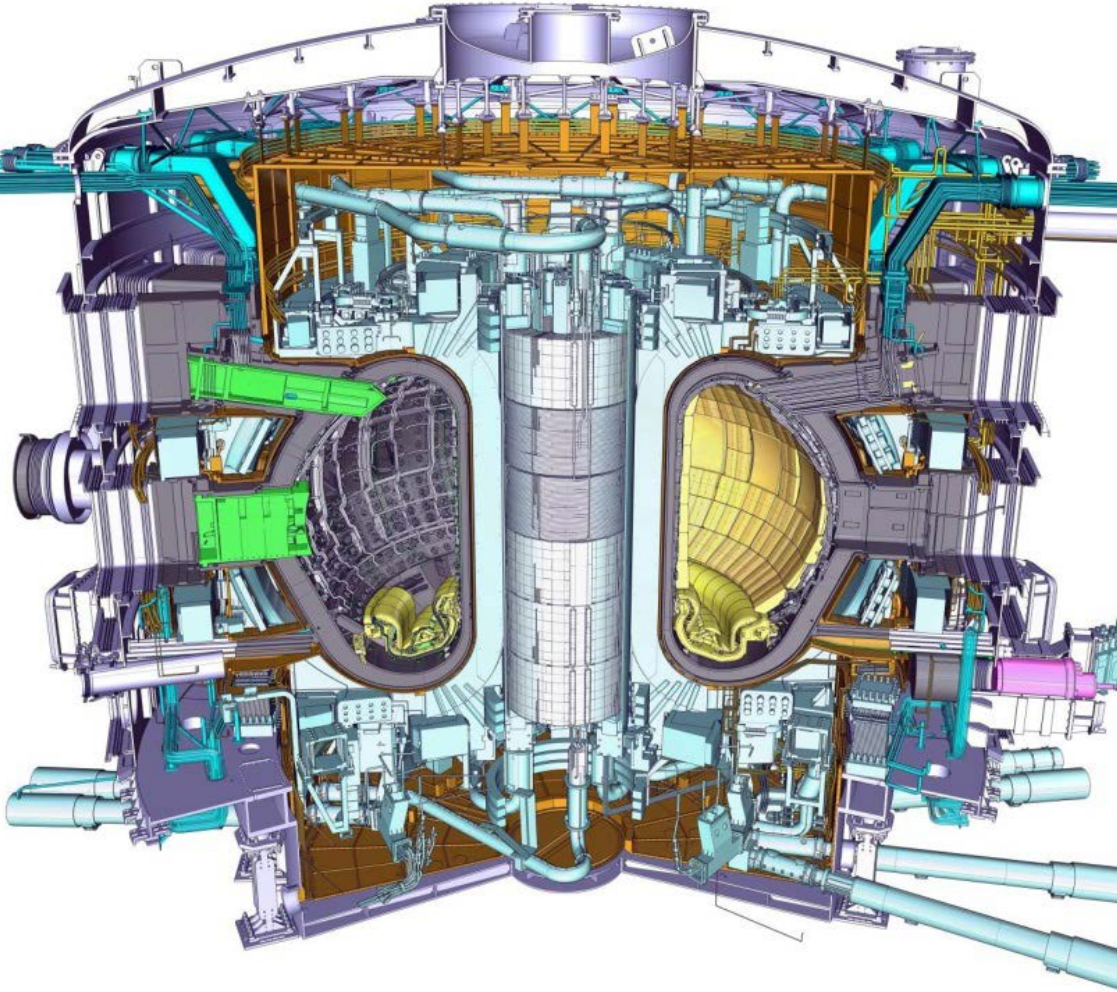
ITER Organization



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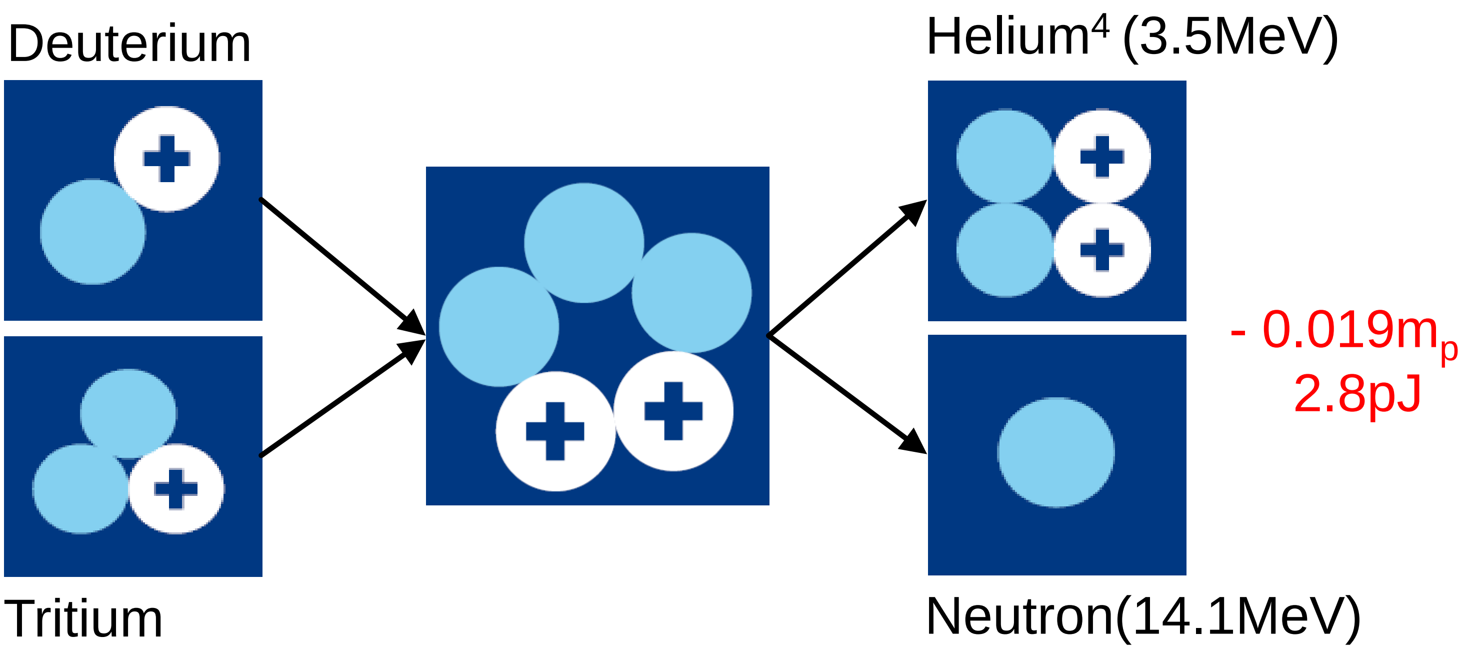
Outline

- **Introduction**
  - **Fusion**
- **ITER Machine**
  - **Status**
- **ITER Future**
  - **Planning**
- **Summary**

ITER site 27/10/2014

Nuclear Fusion

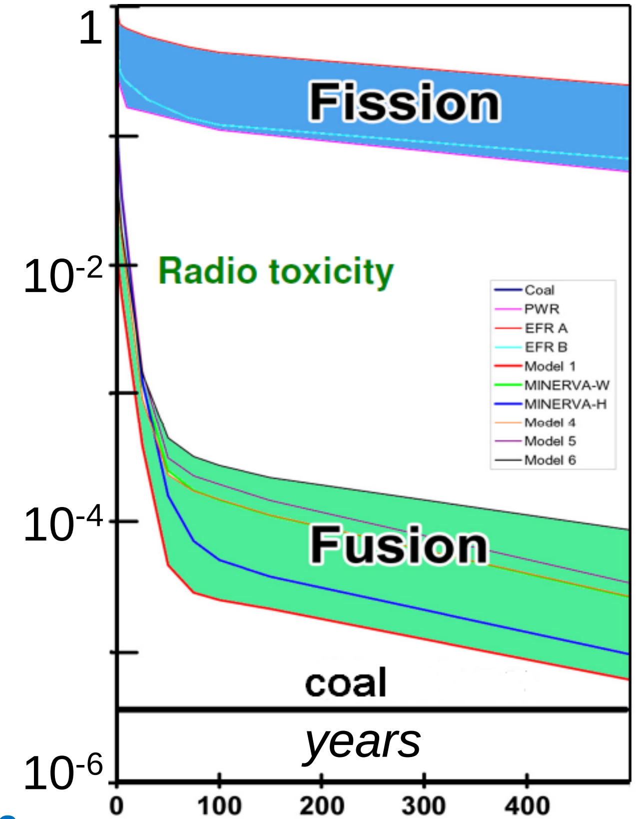
- Easiest fusion reaction:



$^{2}D + {}^{3}T \rightarrow {}^{4}He + n + 17.6\ MeV$

$^{6}Li + n \rightarrow {}^{3}T + {}^{4}He + 4.8\ MeV$

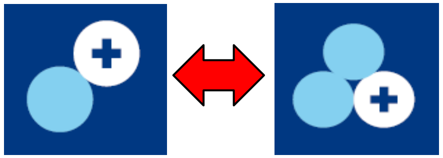
Why Fusion?



- Energy consumption projected to increase by factor 3 by the end of the century
  - Fossil sources are limited
  - Greenhouse gas emissions need to be limited
  - Need to replace fossil sources by renewables and nuclear energy before the end of the century

- Advantages of fusion energy:
  - **Fuel:** Inexhaustible and well distributed on earth
    - Deuterium is plentiful in the oceans, Tritium is to be produced from Lithium
    - 1 gram DT equivalent to 8 tons of oil
  - **Safety:** No run away effect, No fission product to cool, No proliferation
  - **Waste**: Neutron induced activation, low radio toxicity (< 100 years)

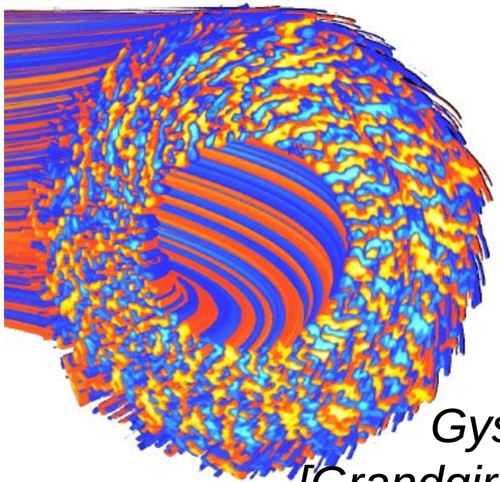
Fusion Conditions (simplified)



- Overcome Coulomb repulsion:
  - high temperature : ~15keV , 150 million degrees
    - Plasma state (unbound ions, electrons, 4th state of matter)
- Significant power production:
  - 500MW / 2.8pJ = $2x10^{20}$ reactions/s
  - n_D n_T = $2x10^{20}$ / ($2x10^{-22}$ $1000m^3$) : n_D = n_T = **$3x10^{19}$ m^{-3}**
- Self sustained (burning plasma):
  - Alpha (i.e. helium) particles heat the plasma, P_{alpha}= P_{fusion} /5
  - W_{plasma} = 2 n T Volume ~ $2x10^{20}$ 15keV $1000m^3$ = 500 MJ
  - Energy confinement time: τ_c = W_{plasma} / P_{alpha} ~ **5 s**

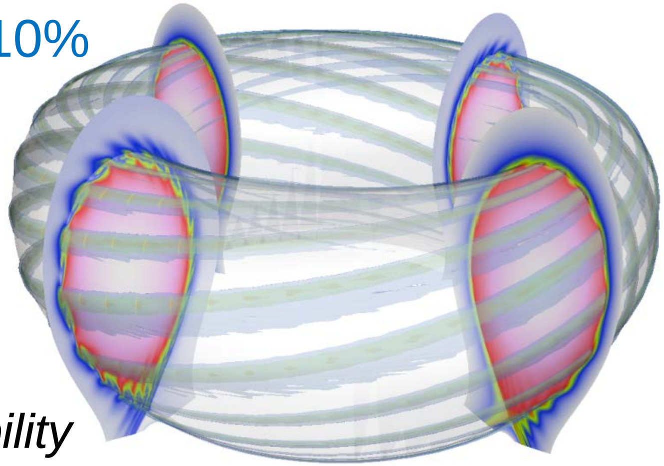
Magnetic Confinement

- Plasma charged particles follow (orbit) magnetic field lines
  - Magnetic confinement
  - Avoid endpoint losses: **torus geometry**
  - Quality of confinement determined by plasma turbulence
    - Improves with machine size and plasma current
      - Experimental (tokamak) scaling: $\tau \sim I_p R^2$



Gysela [Grandgirard]

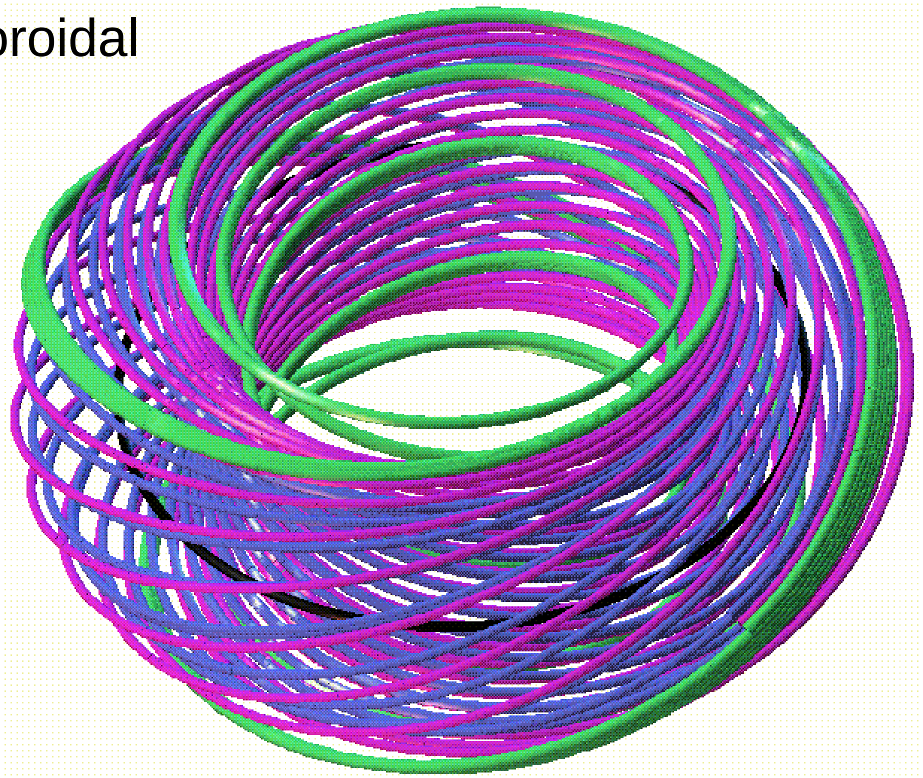
- Stability to global magneto-hydrodynamic instabilities
  - Beta = kinetic pressure / magnetic pressure < 10%
  - Pressure = 2 n T = 5×10^5 Pa ~ **5 atm**
  - Magnetic pressure $\frac{1}{2}B^2/\mu_0$: **B ~ 4T**



ballooning instability

Tokamak

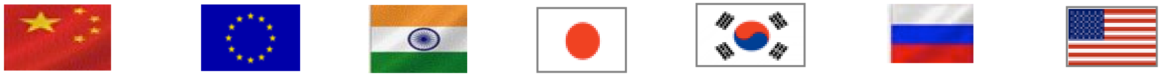
- Toroidal device with helical magnetic field structure
  - dominant toroidal magnetic field
  - poloidal field is created by large toroidal current and poloidal field coils (plasma shaping)
  - toroidal plasma current is inductively driven by central solenoid (primary transformer)
  - plasma is heated by Ohmic heating and "additional" external heating systems



ITER Beginnings

The idea for ITER originated from the Geneva Superpower Summit in *1985* where Gorbachev and Reagan proposed an **international effort to develop fusion energy**…

…"as an inexhaustible source of energy for the benefit of mankind".

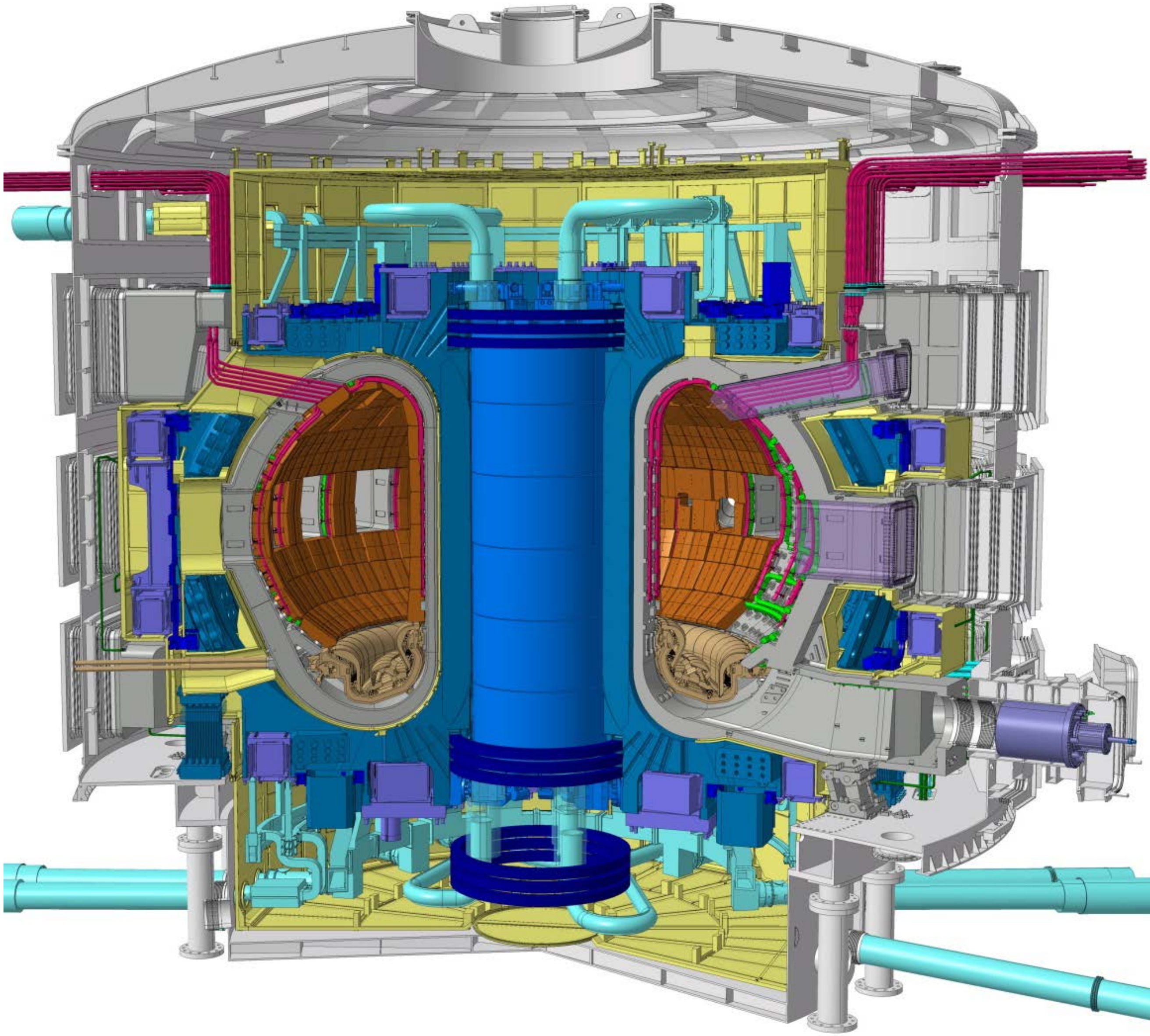


China, Europe, India, Japan, Korea, Russian Federation and the USA sign **the ITER Agreement** on 21 November 2006 in Paris

ITER Mission

- ITER Program objective:
  - to demonstrate the **scientific** and **technological** feasibility of fusion energy for peaceful purposes
  - to design, construct and operate a tokamak experiment at a scale which satisfies this objective
- Key technical Goals:
  - achieve extended burn of a DT plasma with dominant self heating
    - Fusion power amplification **Q=10** for 400 s (P_{in}=50MW, P_{fusion}=500MW)
  - develop steady-state fusion power production as ultimate goal
    - **Q=5** for 3000 s
  - integrate and test all essential fusion power reactor technologies and components
    - test concepts for a tritium breeding module
  - demonstrate safety and environmental acceptability of fusion

ITER Tokamak

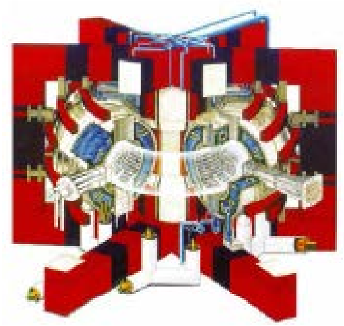


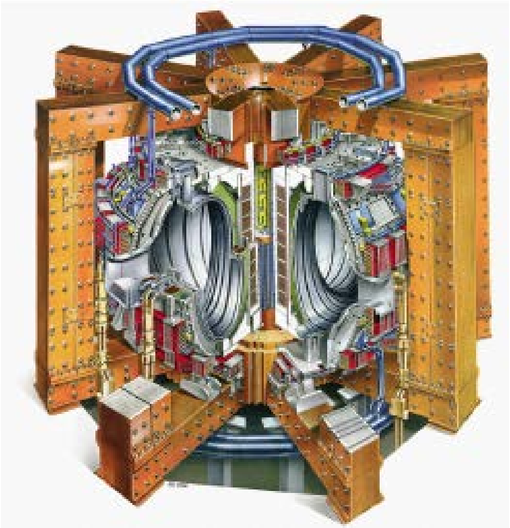
Height	29 m
Diameter	28 m

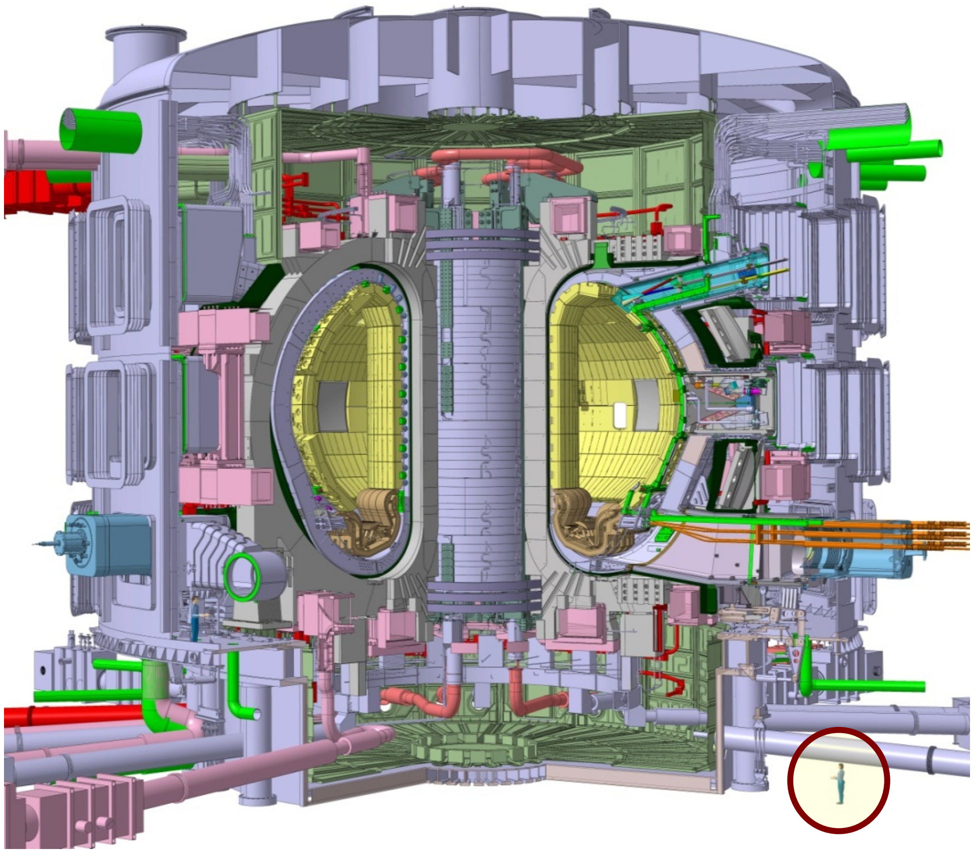
Plasma Parameters:

major radius	6.2 m
minor radius	2.0 m
magnetic field	5.3 T
current	15 MA
Volume	830 m^3

ITER – the next step







Tore Supra

Vol~25 m^3, I_p~1 MA

P_{fusion} 0 MW

t_{plasma} ~ 400 s

JET

Vol~80 m^3, I_p~3 MA

P_{fusion} ~16 MW, 1s

t_{plasma} ~30 s

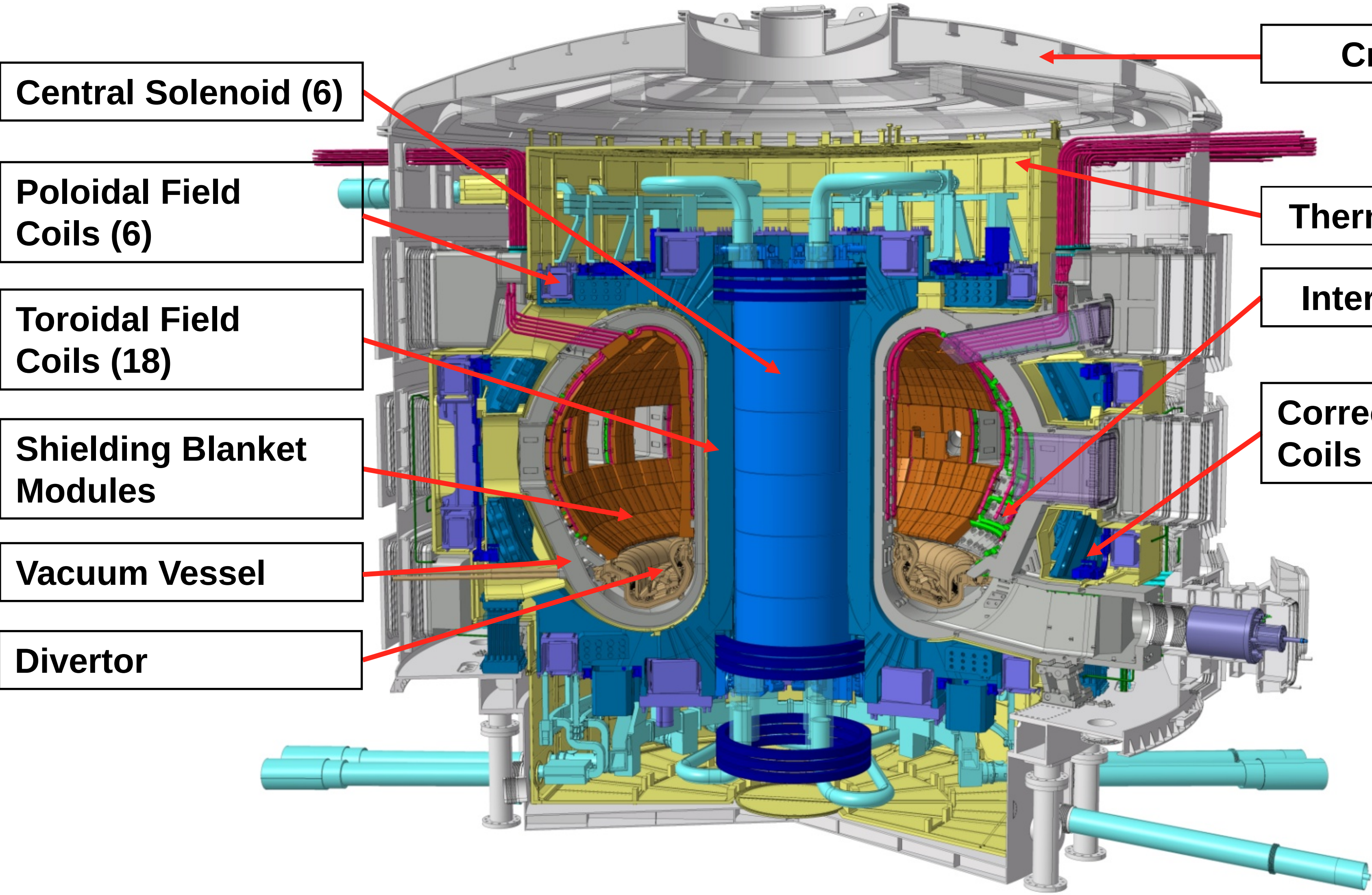
ITER

V_{plasma} 830 m^3, I_p = 15 MA

P_{fusion} ~500 MW, 300 – 500 s

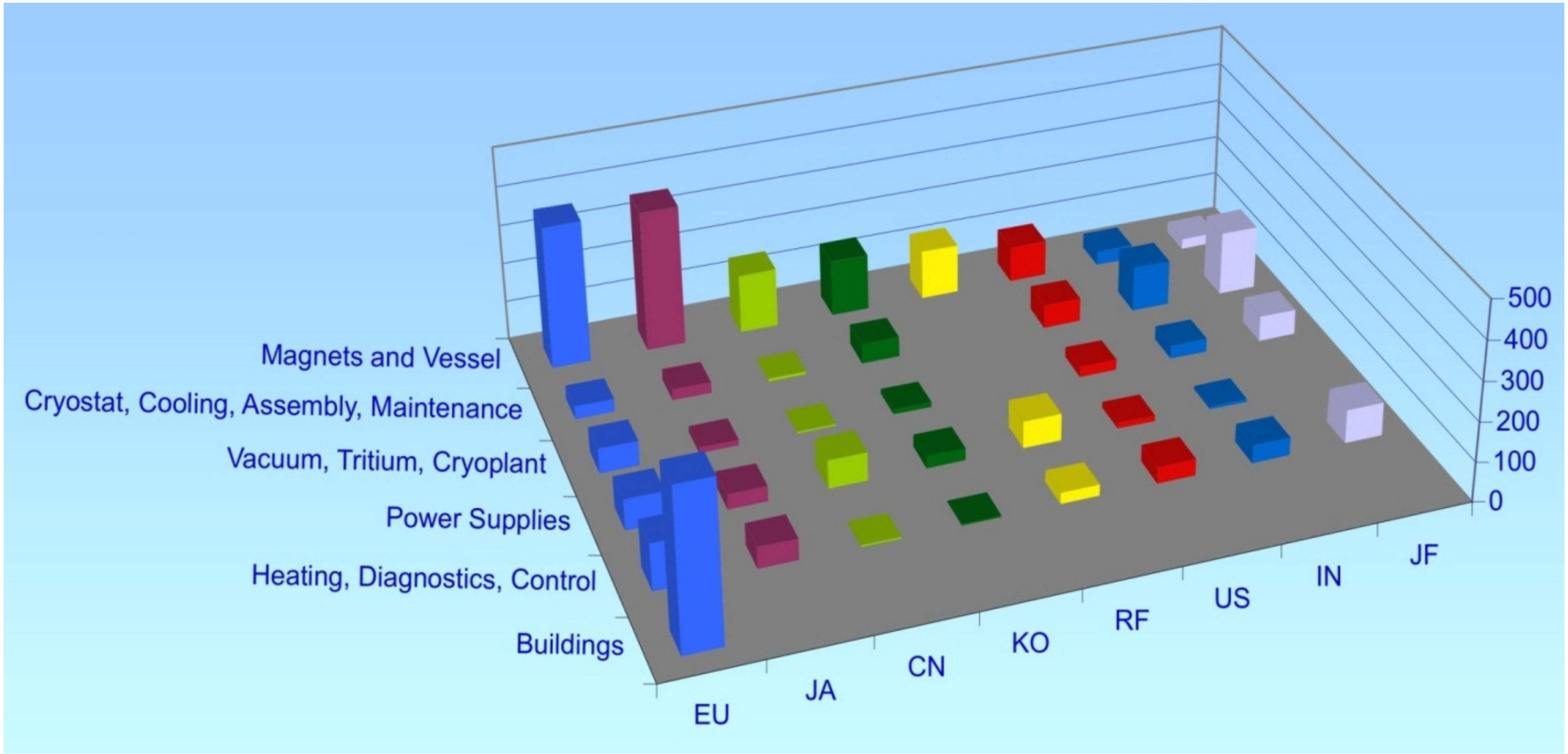
t_{plasma} ~ 600 – 3000 s

ITER - Major Components



Procurement Distribution

- A unique feature of ITER is that almost all of the machine will be constructed through **in kind procuremen**t from the Members
  - Procurement packages are shared between China, India, Japan, Korea, Russia and the United States (9%). Europe's share, as Host Member, is 45%

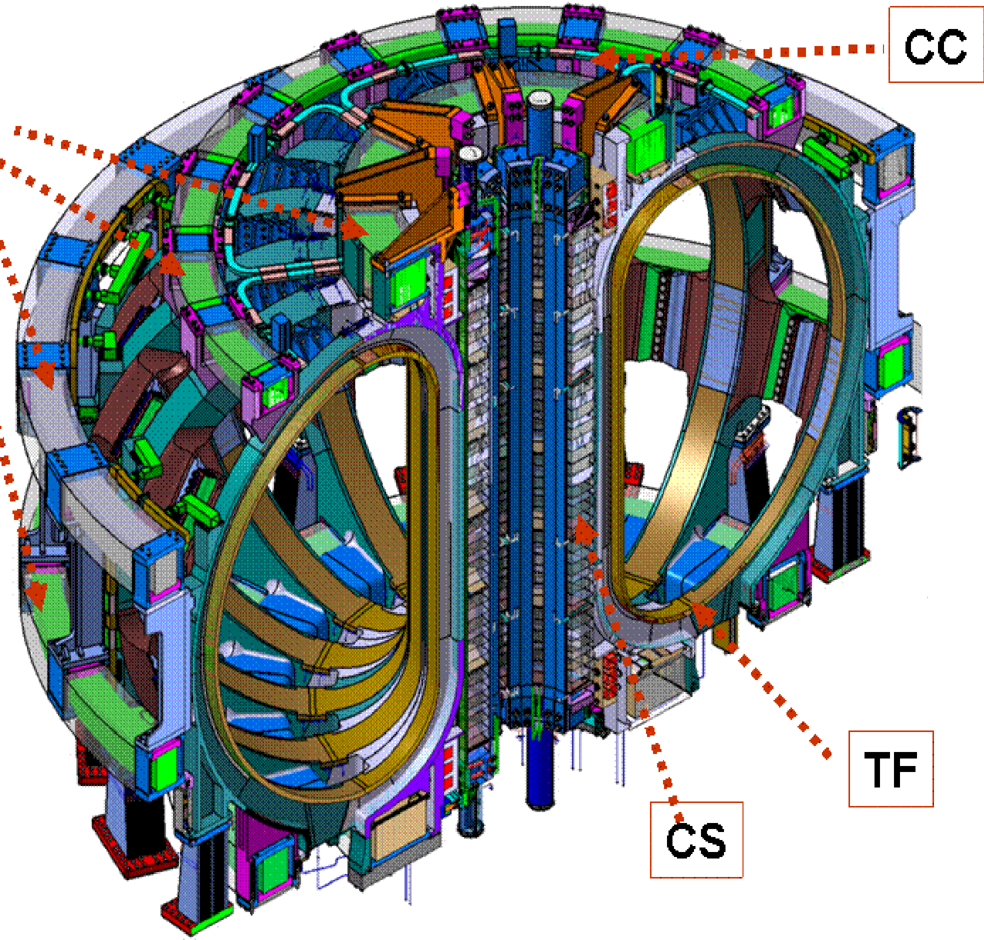


ITER - Magnet Systems

48 superconducting coils

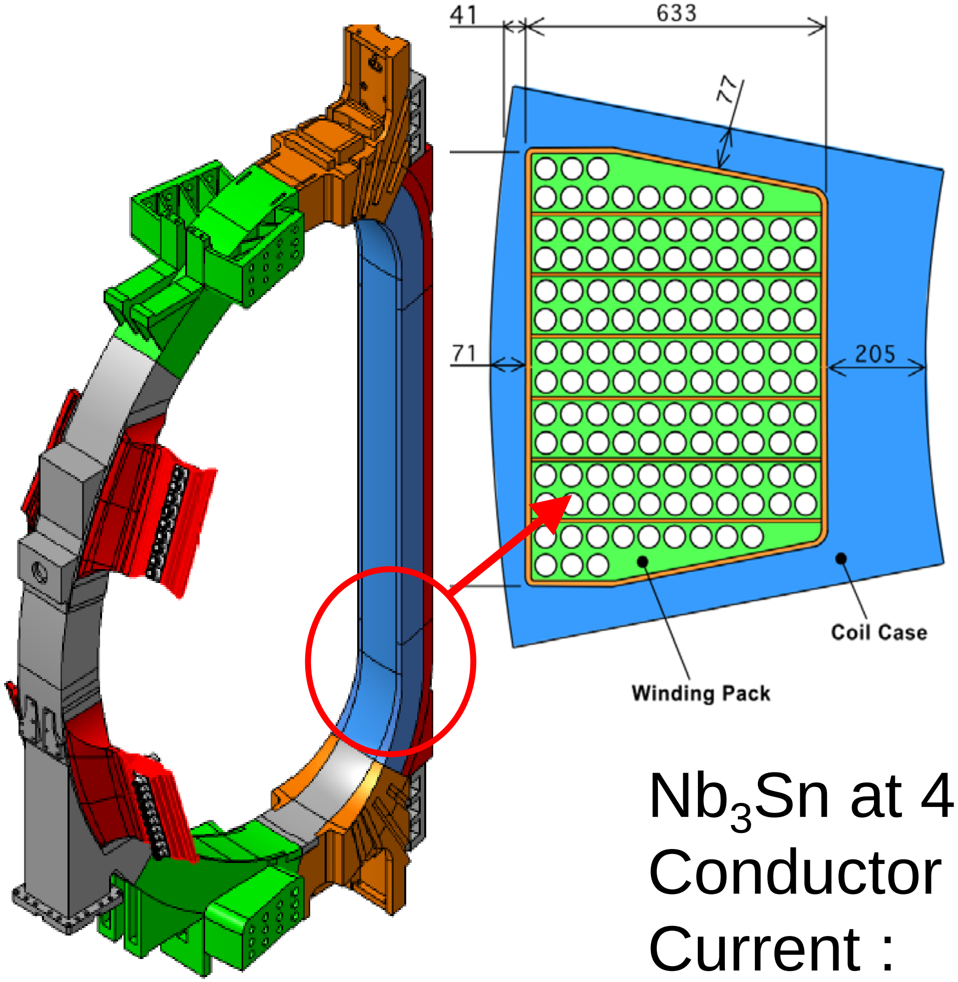
- 18(+1) Toroidal Field coils
- 6 Central Solenoid modules
- 6 Poloidal Field coils
- 9 pairs of Correction Coils

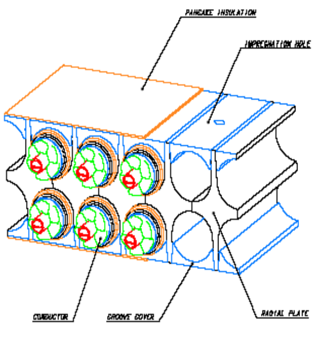
- Energy **51 GJ**
- Weight 10.360 ton



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

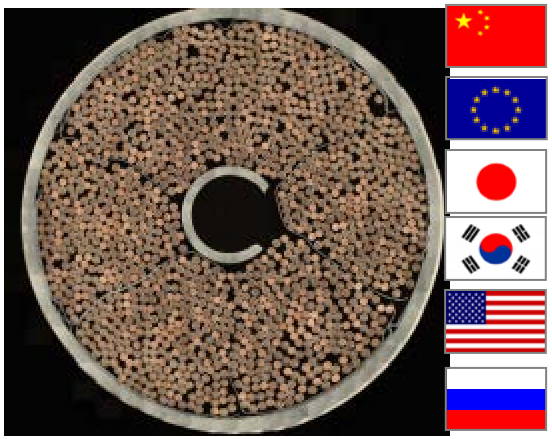
Toroidal Field Coils





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

Nb_3Sn at 4K
Conductor : 82 km
Current : 63.4 kA
Turns : 144
Max field : 11.8 T

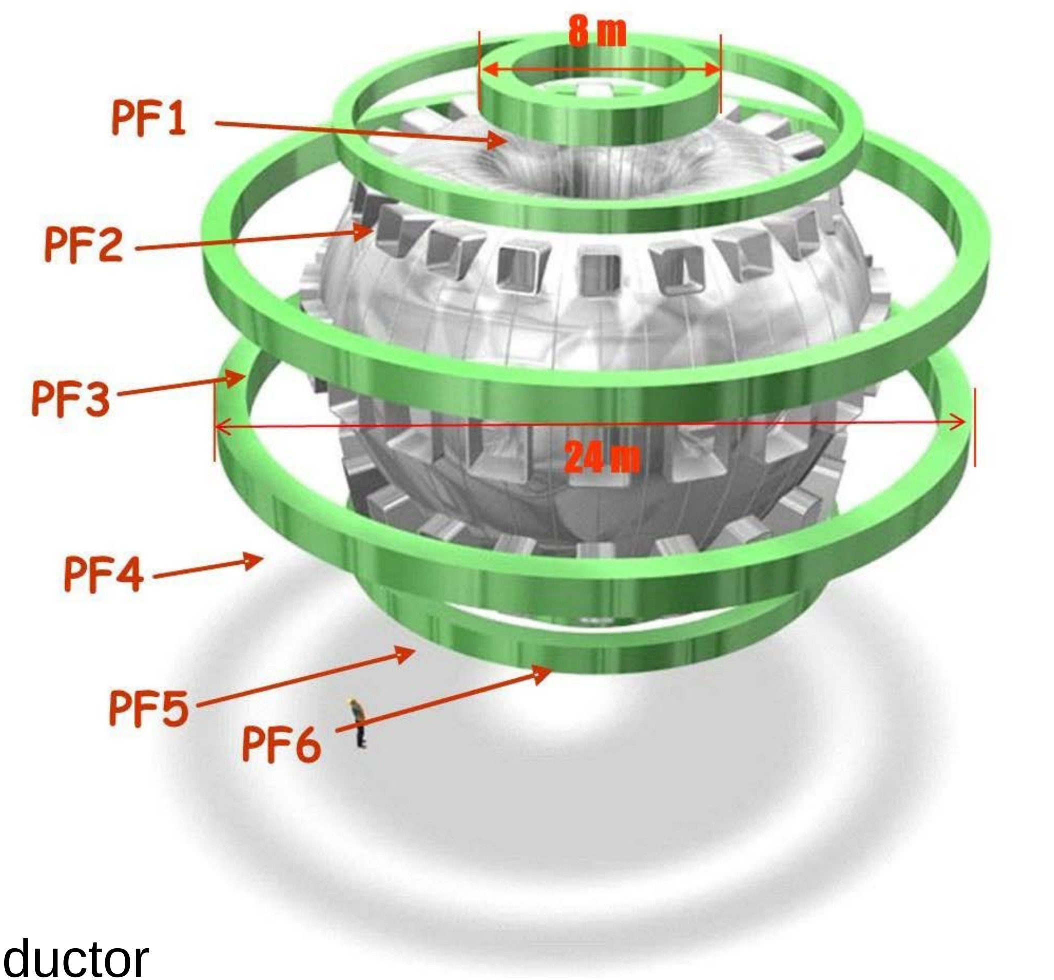


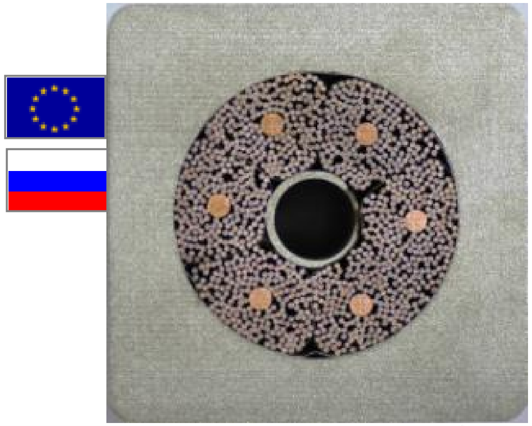
Toroidal Field Coils

Poloidal Field Coils

- Poloidal Field (PF) coils for plasma shaping and position control

  - 6 coils (EU, RF) 
  - Up to 25 m diameter
  - NbTi conductor
  - 6.8 T (peak PF field)
  - 55 kA (peak current)
  - PF2-6, manufactured on-site
  - PF3: 24.5 m diameter, 386 t



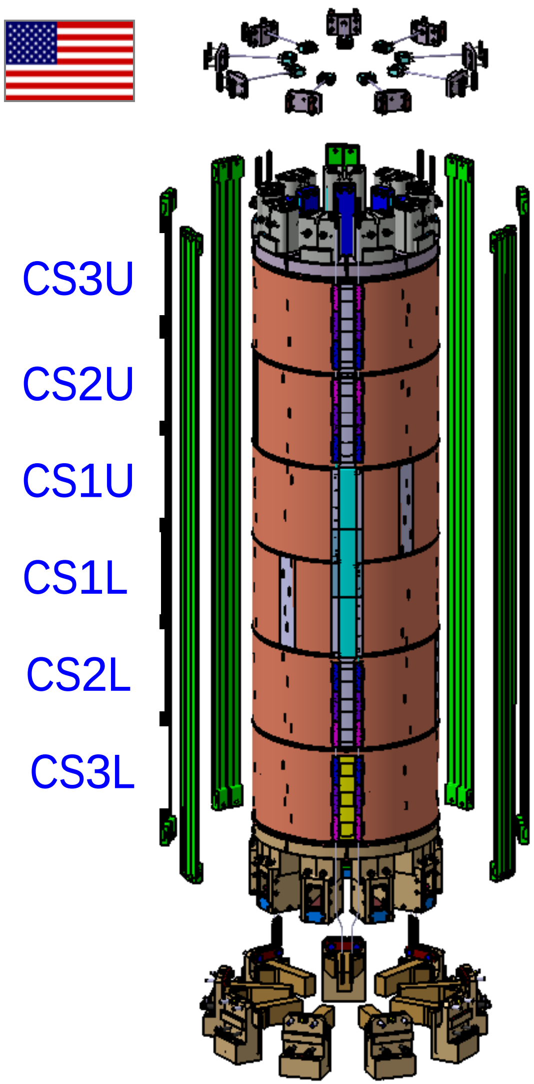


NbTi conductor

Poloidal Field Coil Building

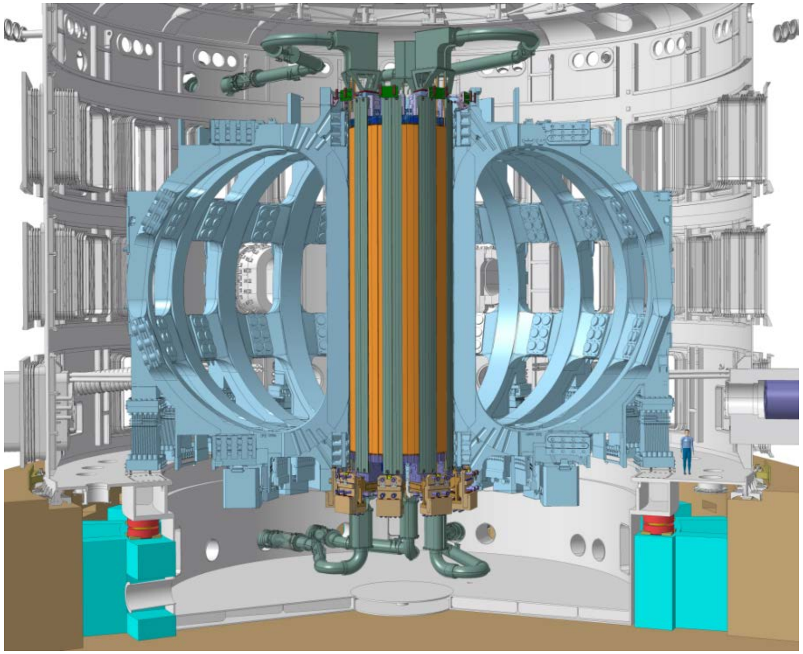
- PF coils to large to transport, require onsite building
  - 257 (L) x 49 (W) x18m (H), completed 2011

Central Solenoid



CS Coil Stack for the induction plasma current and shape control

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

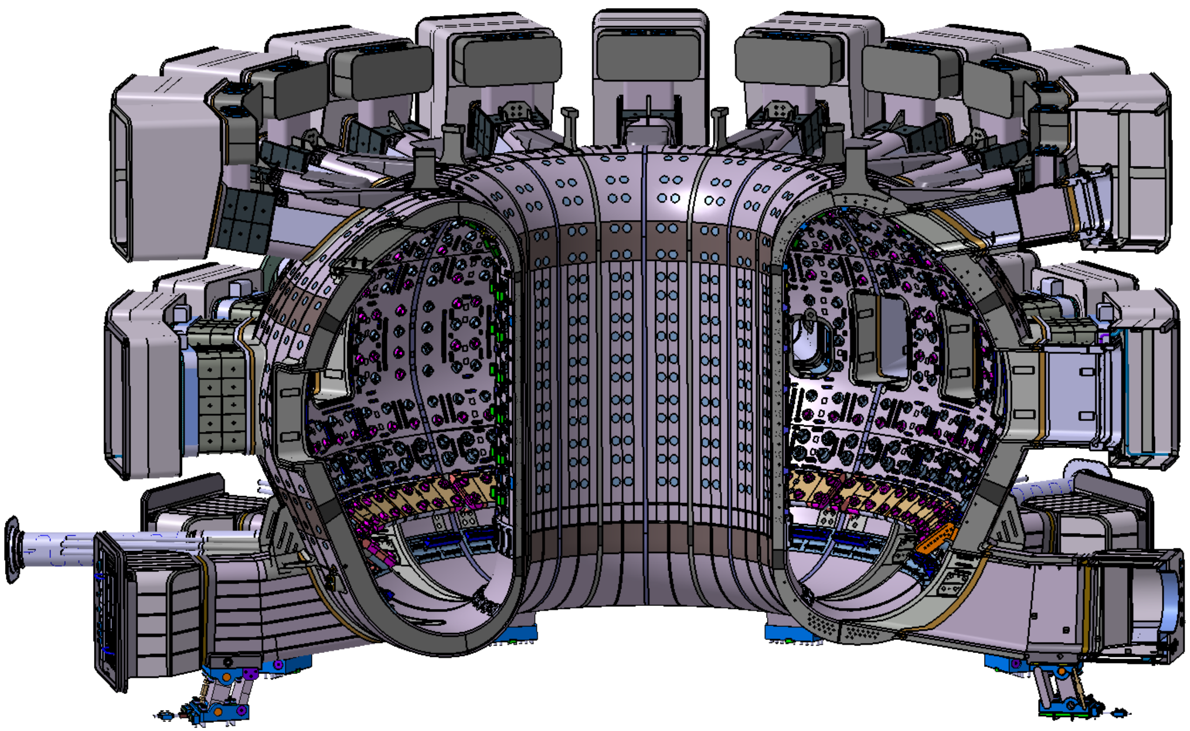


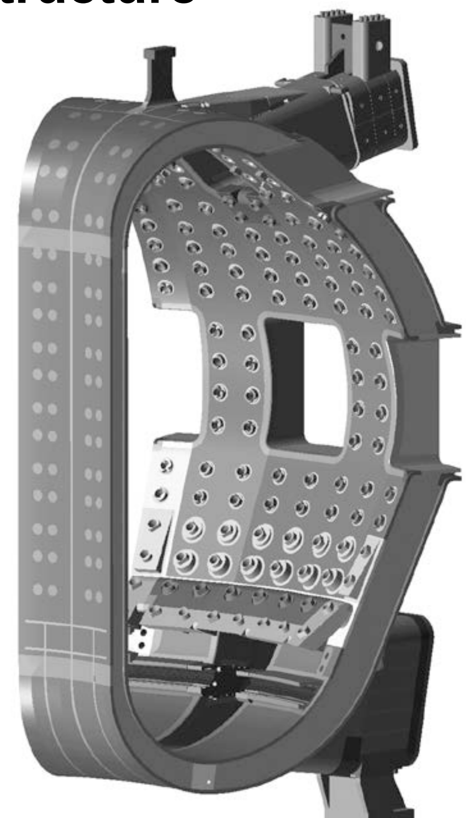
Central Solenoid: Tie Plate

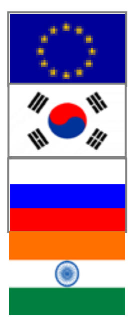
Tie plates holding solenoid modules (forces ~60MNewton)
13m forged single piece

Vacuum Vessel

- **Vacuum Vessel is a double-walled stainless steel structure**
  - provides primary tritium confinement barrier

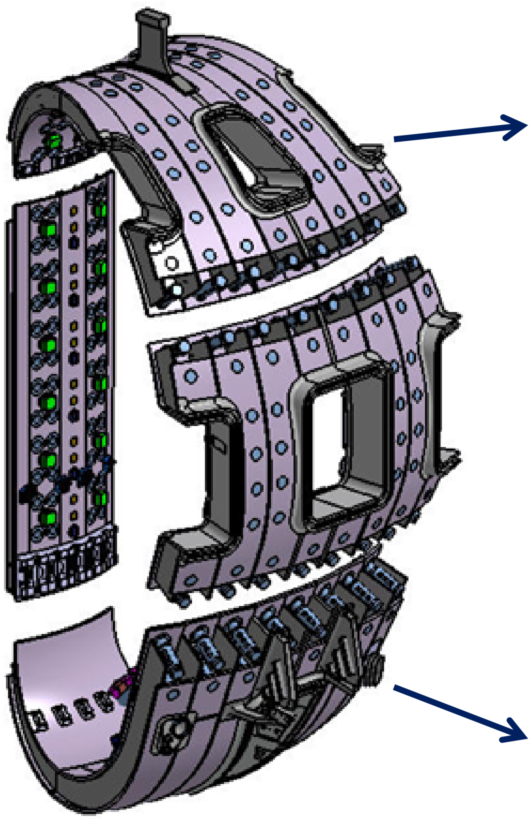




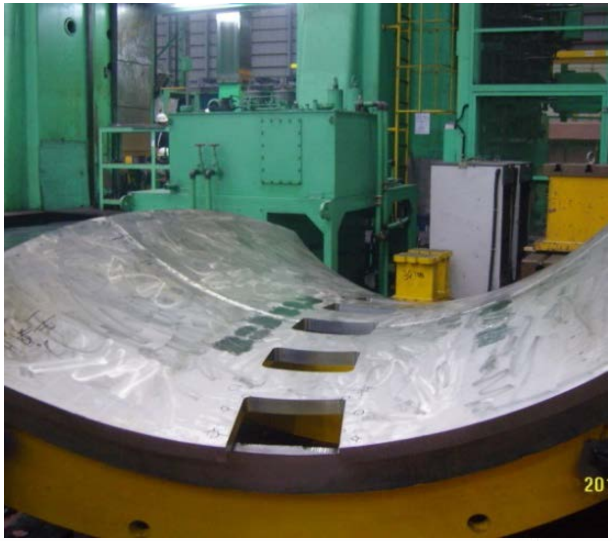


Major dimensions		Weight (ton)	
Outer diameter (m)	19.4	Main Vessel	1611
Height (m)	11.4	Shielding	1733
Double wall thickness (m)	0.34–0.75	Ports	1781
Interior surface (m^2)	850	Supports	111
Interior volume (m^3)	1600	Total	5236

Vacuum Vessel Manufacturing

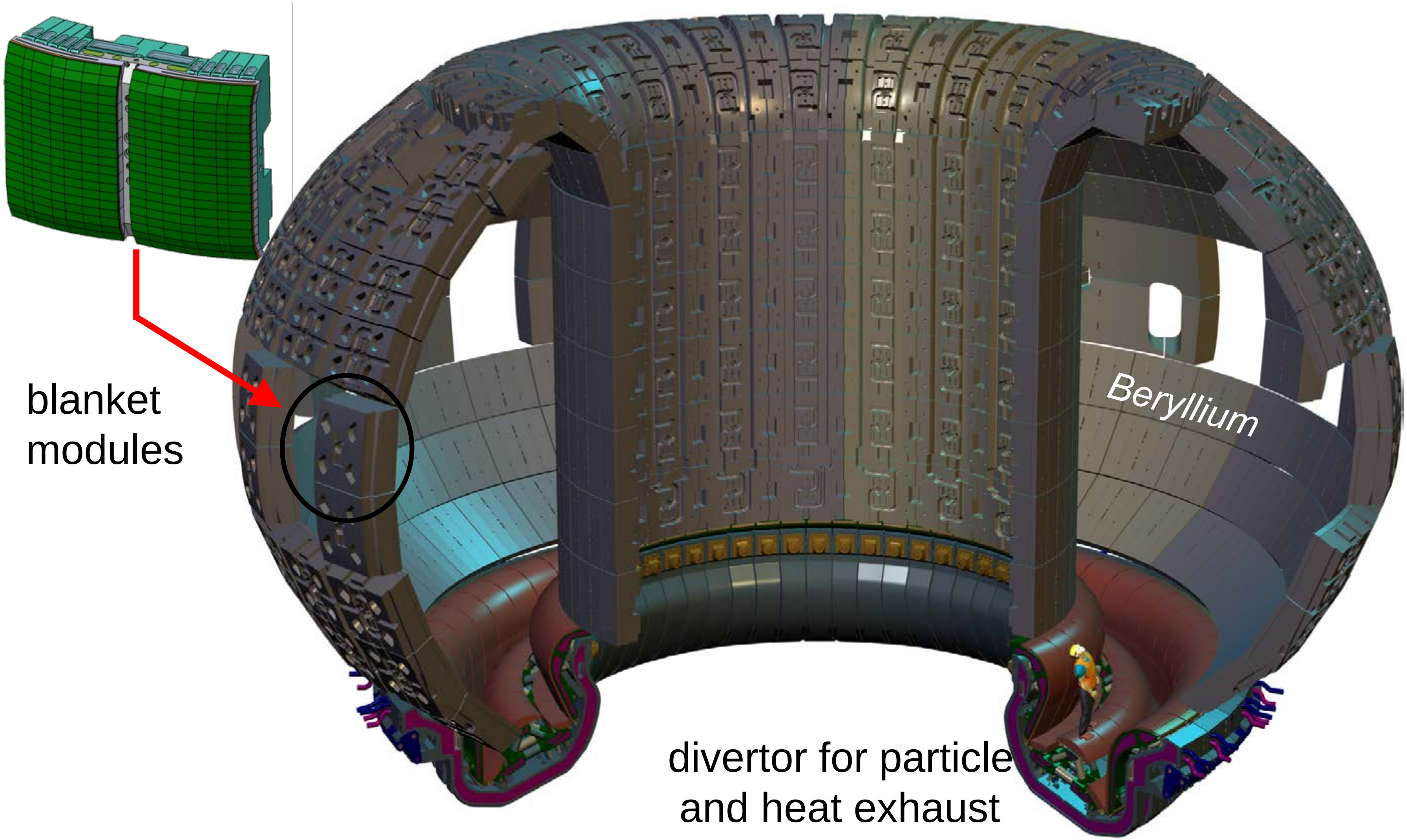


VV Sector: 4 Segments



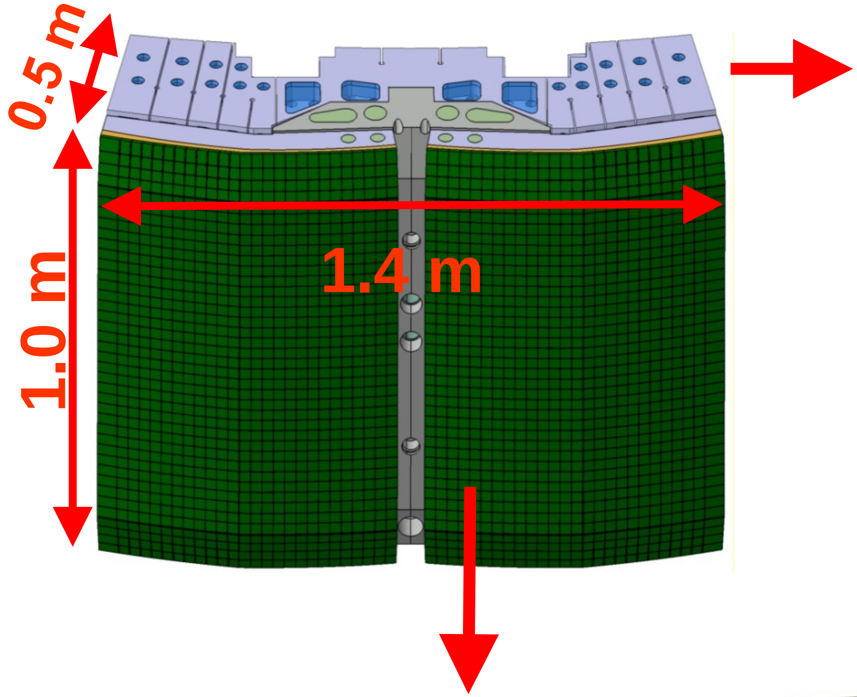
Principal plasma-facing components (PFC)

first wall/blanket for heat exhaust, impurity management, nuclear shielding

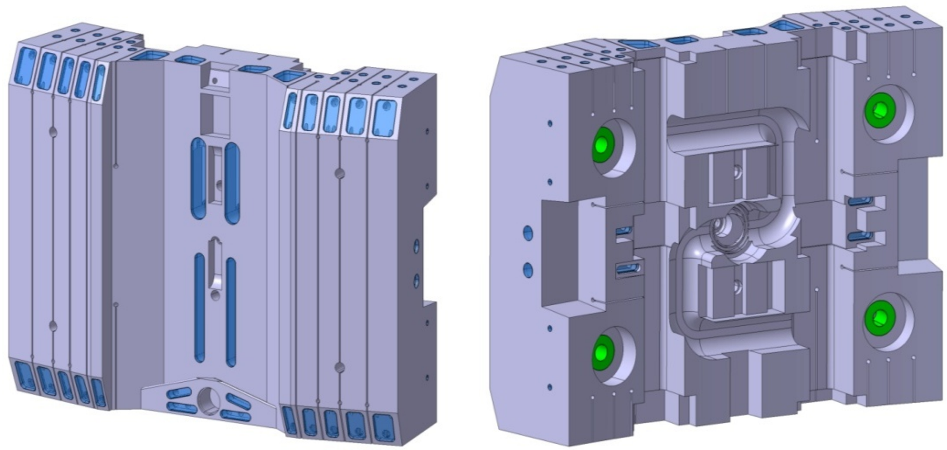


First wall: blanket modules (BM)

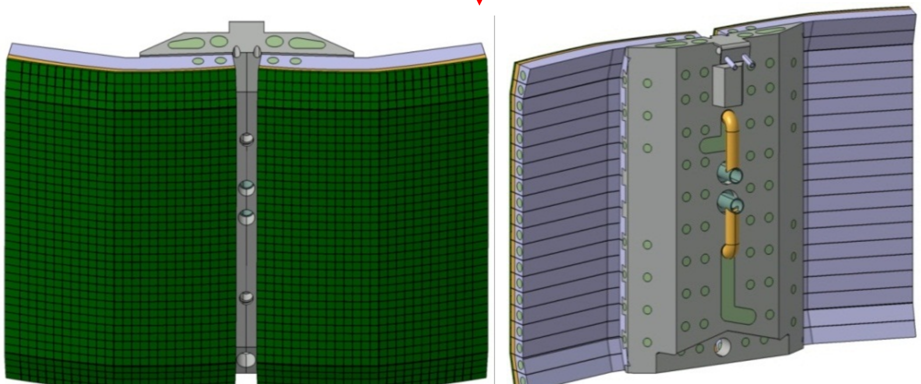
two main components



Neutron shielding:
Semi-permanent massive **Shield Blocks** (SB): ~3.5±0.5 tonnes

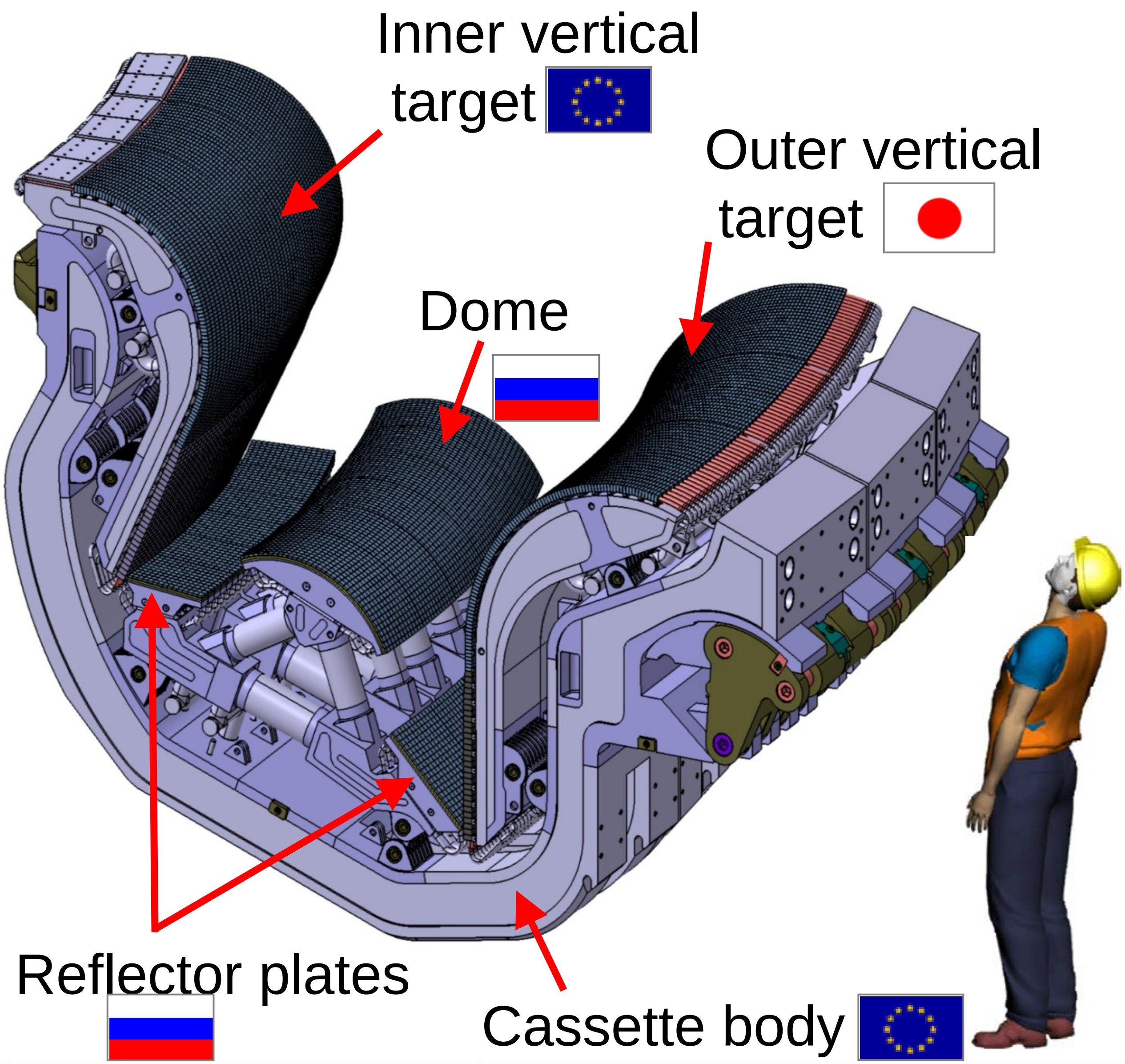


Plasma-facing surfaces: separable shaped **First Wall Panel** (FW), armoured with **Be** tiles



Total number of BMs: 440
Total mass: ~1800 tonnes
SB: CN (50%), KO (50%)
FWP: CN (10%), EU (50%), RU (40%)

Divertor



54 divertor assemblies (~8.7 tonnes each)

4320 actively cooled heat flux elements

Bakeable to 350°C

All divertor plasma-facing components will be in tungsten (W)

T_{melt}= 3422 °C

$T_{recrystal}$~1400 °C

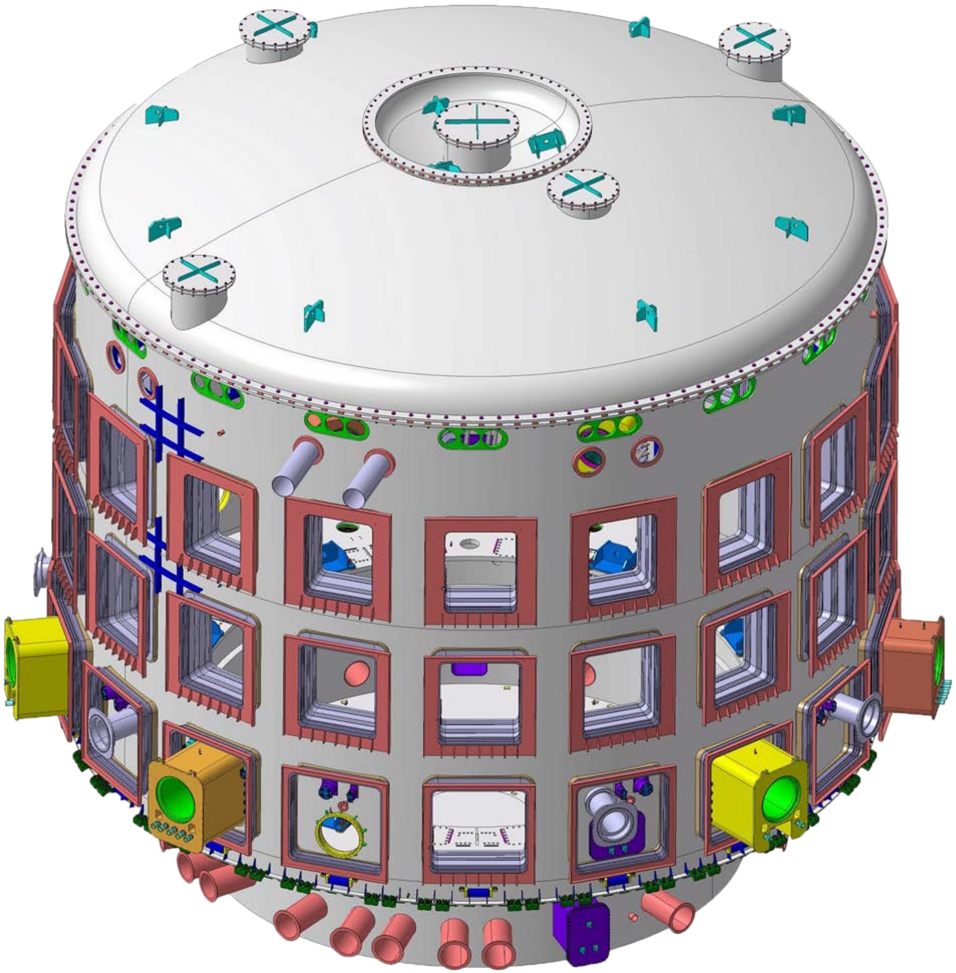
Operating T ~1200 °C

Steady heat load: 10MWm^{-2}

Cryostat

- Cryostat reduces the transfer of heat to superconducting coils at cryogenic temperatures
  - Secondary containment barrier
  - Transfers loads to tokamak complex floor

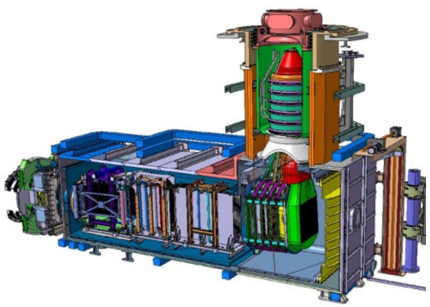
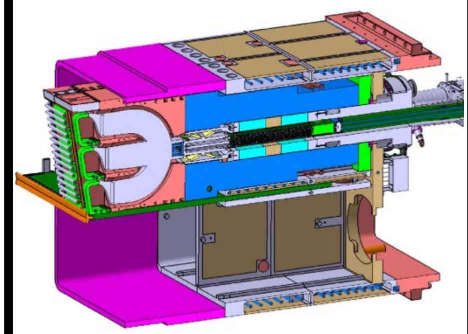
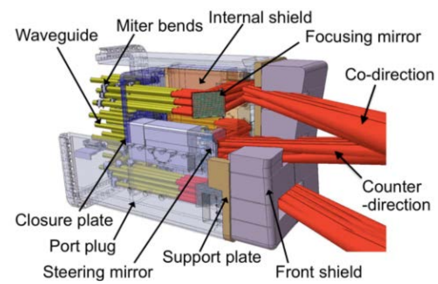
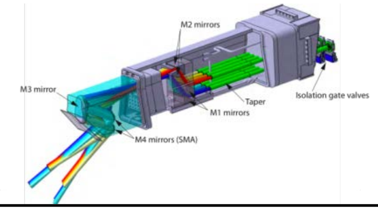
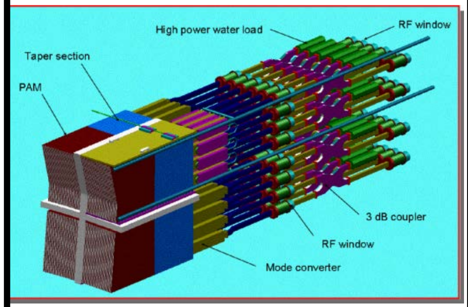
- Height 29, diameter 28m
- 304L Stainless steel
  40 – 180 mm thick
- Weight ~3500 tonnes
- Vacuum pressure: <10-4 mbar



- **IN-DA signed PA September 2011**
- **Contract awarded in August 2012**

Cryostat manufacturing

ITER Heating and Current Drive Systems

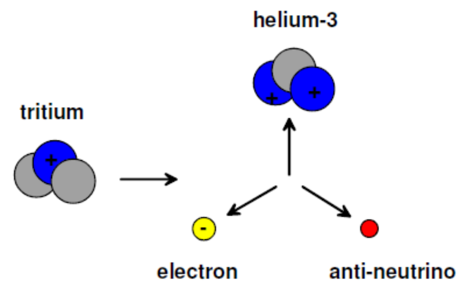
NB	IC	EC	LH
Neutral Beam - 1 MeV	Ion Cyclotron 40-55MHz	Electron Cyclotron 170GHz	Lower Hybrid ~5 GHz
		  	
33MW* +16.5MW#	20MW* +20MW#	20MW* +20MW#	0MW* +40MW#
Bulk current drive	Sawtooth control	MHD control	Off-axis current drive

*Baseline Power

#Possible Upgrade

Deuterium-Tritium Fuel Cycle

- Tritium is a pure β-emitter (E_{max} = 18 keV)
- Half life $t_{1/2}$ = 12.323 years
- 1 gram T = 324 mW decay heat
- Main radiological hazard through ingestion



ITER Fueling systems:

- Gas Injection
- Solid Pellet Injection
- Neutral Beam Injection

Plasma T throughput	***~ 1 kg/hr***
Plasma T inventory	***~ 0.2 g***
T inventory on-site	***< 4 kg***
Fuel cycle inventory	***~ 2 kg***

- The ITER Tritium–plant is a 7-floor nuclear building: H 35, L 80, W 25 m.
- For ITER tritium will be imported (is extracted from CANDU water; typical production ~ 100-150 g T/yr for a 600 MW CANDU reactor)

About 56 kg tritium is required per $GW_{thermal}$Yr of DT Fusion power → Need to produce T and collect it on-line:

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

Tritium Breeding Blanket Testing in ITER

TBM Program:

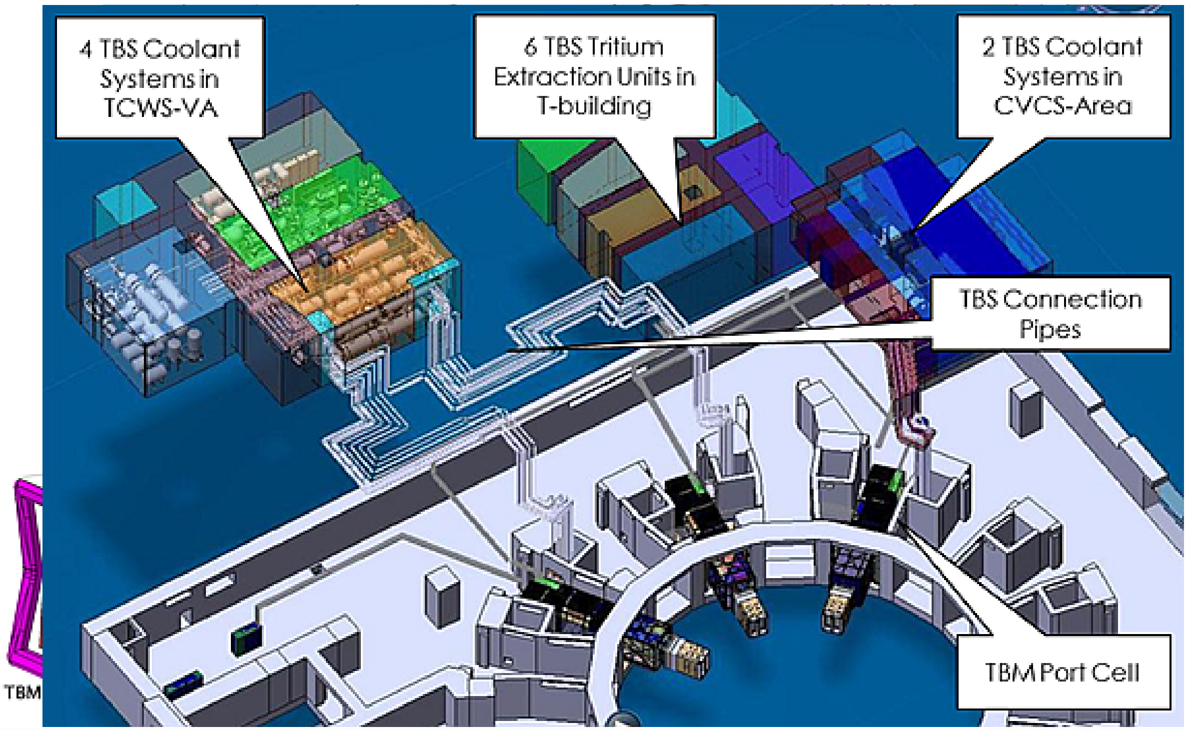
- ✓ **5 ITER members**
- ✓ **3 Equatorial ports**
- ✓ **6 Test Blanket Systems**
- ✓ **4 Test Phases**

→ *ITER as "User Facility"*

EU:	**HCLL** , Helium-cooled Lithium Lead **HCPB**, He-cooled Pebble Bed
JA:	**WCCB**. Water-cooled Ceramic Breeder
KO:	**HCCR**, Helium-Cooled Ceramic Reflector
CN:	**HCCB**, He-cooled Ceramic Breeder
IN:	**LLCB**, Lithium-Lead Ceramic Breeder

Status October 2014:

- 4 out of 6 Test Blanket Module Arrangements have been signed
- Conceptual Design Reviews for 1 TBS and the Connection Pipes
- TBSs to be installed in 2nd Assembly Phase



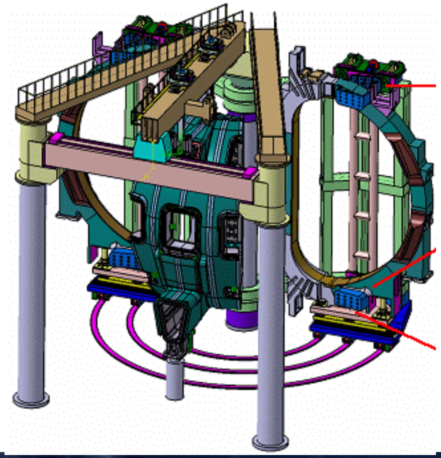
Transport ITER Components

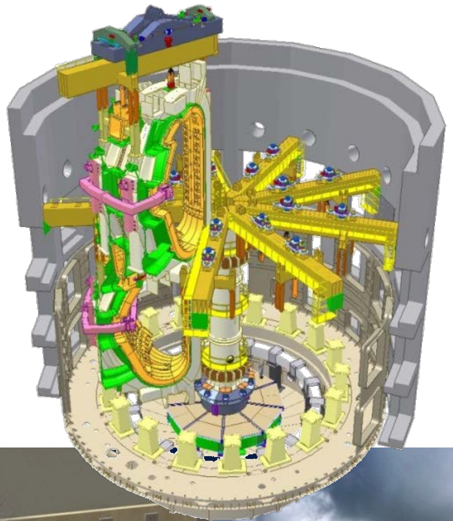
- Largest and heaviest ITER components, arriving by sea, require special nightly convoys (~4 nights)
  - 104 km over small roads, about 200 convoys

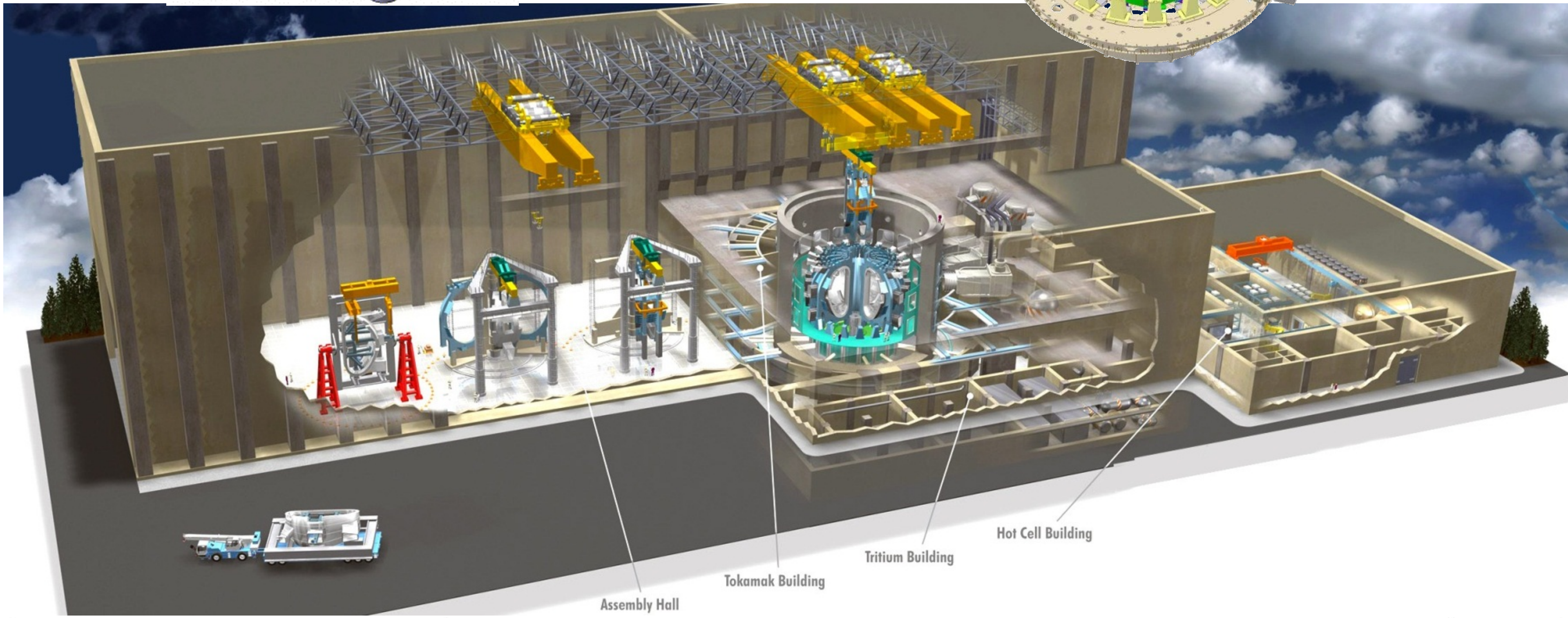
ITER Test Convoys

- The ITER Test Convoys took place on 16-20/9/2013 and 31/3 - 8/4/2014
  - Convoys were 46 metres long, 9 metres wide and 10 metres high, weighing 800 tons

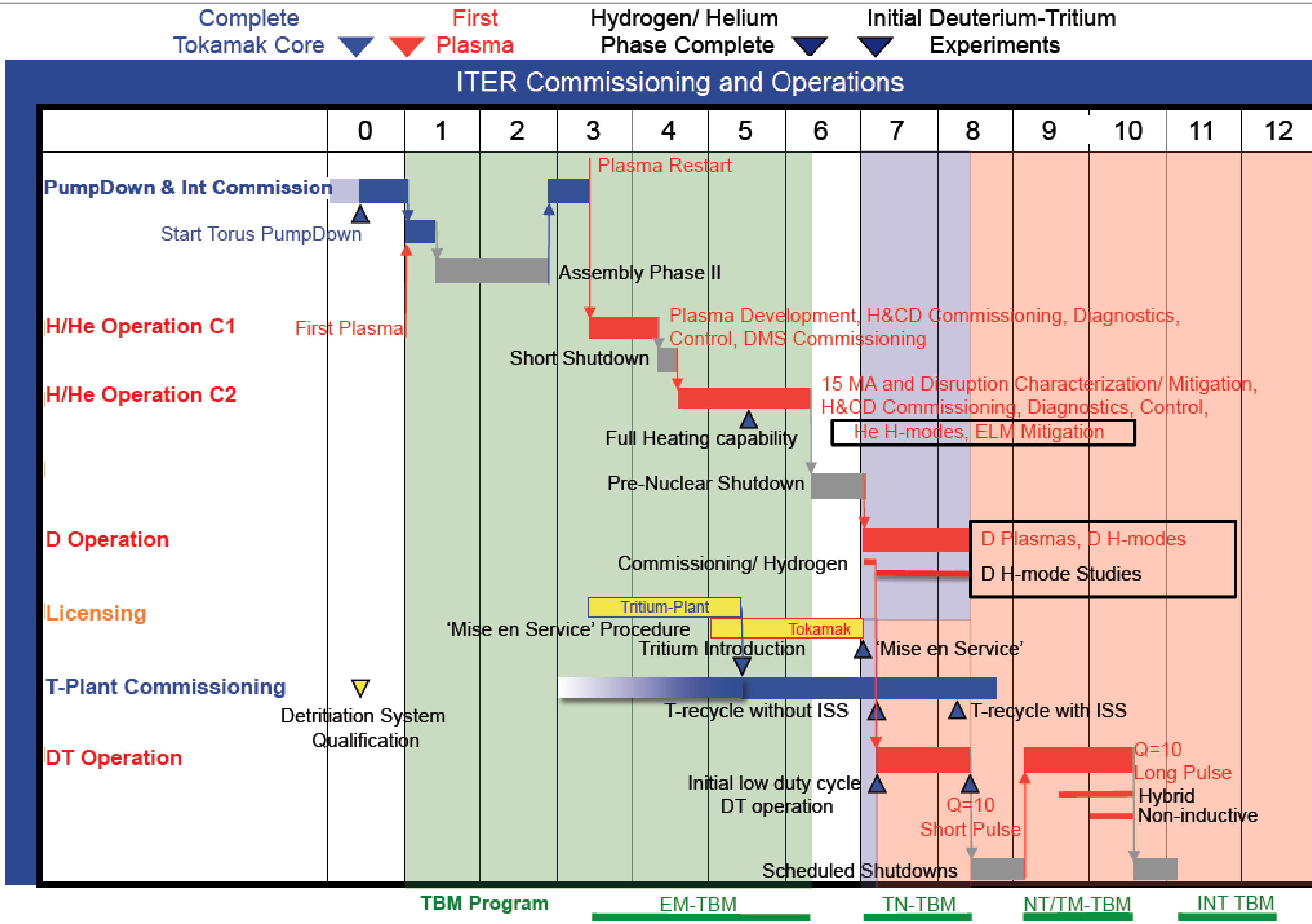
ITER Assembly





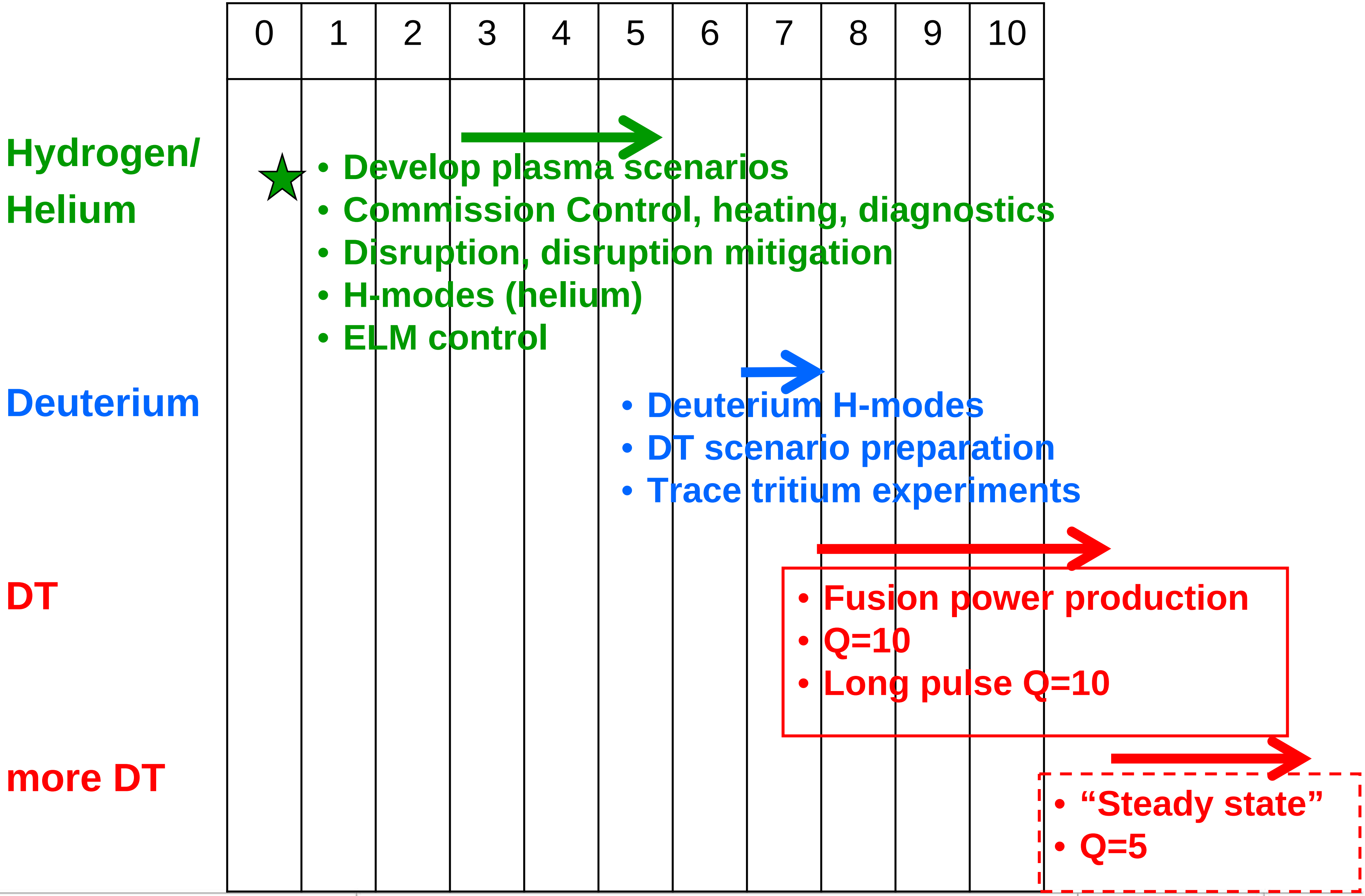


ITER Research Plan



- In reference schedule First Plasma corresponds to 2020-2021
- Schedule under review → new schedule to be submitted to ITER Council in June 2015

ITER Research Plan



ITER Nuclear Licensing

ITER will be licensed as a Basic Nuclear Installation (INB)

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

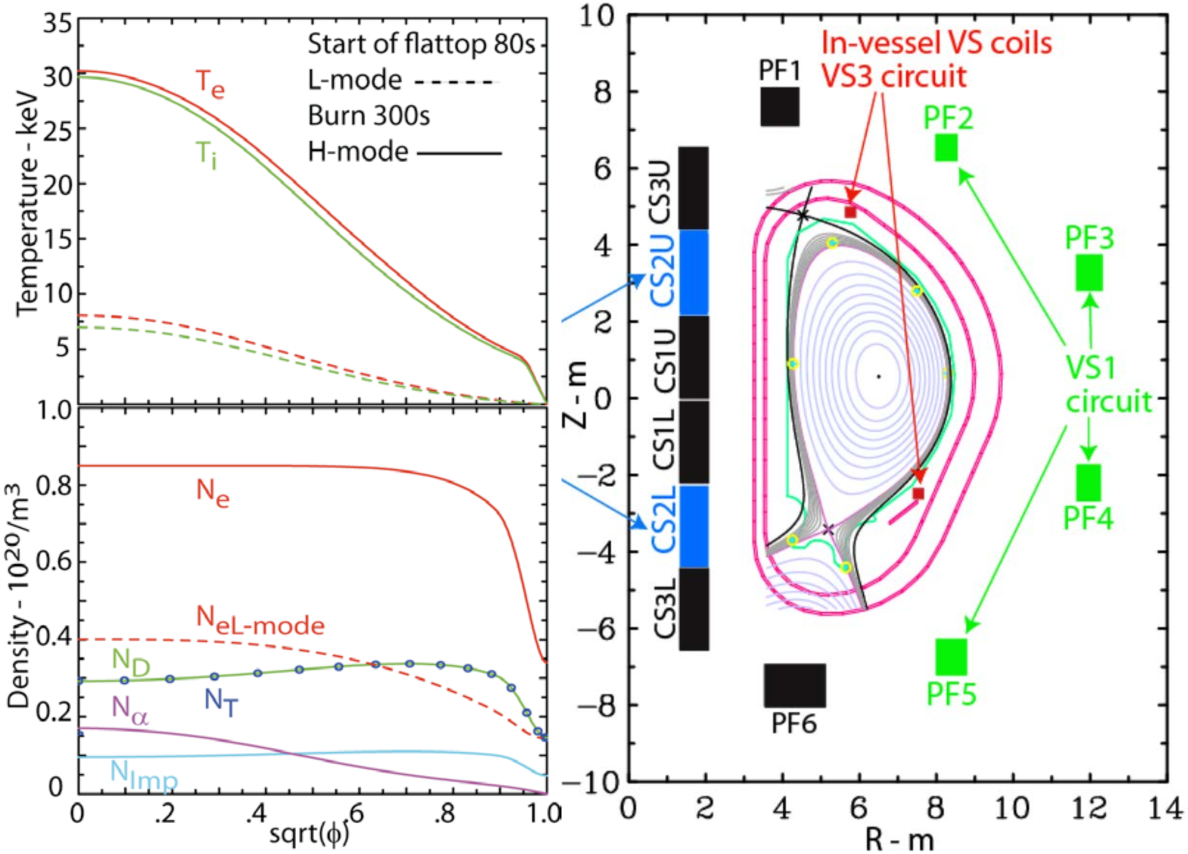
A LA POURSUITE DU PROCESSUS D'AUTORISATION DE CREATION DE L'INB ITER

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**

ITER Plasmas

- Q=10, 15MA, ELMy H-mode
  - 350MJ, 800m^3
  - P_{heat} ~ 40-50MW
  - P_{fusion} ~ 400-500MW
  - flattop 300-500s
- High density
  - close to density limit
  - Pellet fuelling
    - Gas fuelling inefficient
- Detached divertor
  - P_{sol}=100MW
  - Impurity seeding (N_2/Ne)



- Also: hybrid and advanced scenarios

ITER Site

Summary

- ITER is designed to:
  - achieve extended burn of a DT plasma with dominant self heating
    - Fusion power amplification **Q=10** for 400 s (P_{fusion}=500MW)
  - develop steady-state fusion power production as ultimate goal
    - **Q=5** for 3000s
  - integrate and test all essential fusion power reactor technologies and components
    - Tritium breeding blankets

- ITER construction well under way:
  - Buildings on the ITER site
  - Components at the domestic agencies of the 7 ITER Members

For more information:
www.iter.org
http://www.youtube.com/user/iterorganization

ITER Beginnings

- 1985 Geneva summit, Gorbachov-Reagan
  - **developing fusion energy for peaceful purposes**
- 1988-1990 Conceptual design activity
  - EU, USSR, JP, US
- 1991-1998 Engineering design activity
  - Garching, Naka, San-Diego
- 1998-2001: reduced cost option, EU, USSR, JP
- 2001,2002: site proposals EU,JP
- 2003: China, Korea new members, US rejoins
- 2005: India joins,
  site decision: Cadarache, France
- 2006: ITER agreement signed
- 2007: ITER Organization

Deuterium-Tritium Fuel Cycle (2)

Ingredients for fusion energy systems with Tritium self-sufficiency:
add ^{6}Li as close as possible around the plasma to capture neutrons

Main available T-breeders *(Li-based compounds):*

- Solid Li-Ceramics: Li_2O, **Li_4SiO_4, Li_2TiO_3**
- Liquid Lithium *(natural 7.5% 6Li)*
- Liquid Eutectic **LiPb-alloy** *($T_{melting}$: 235°C)*
- Liquid Molten Salts : FLiBe, FLiNaBe

Neutron multipliers:

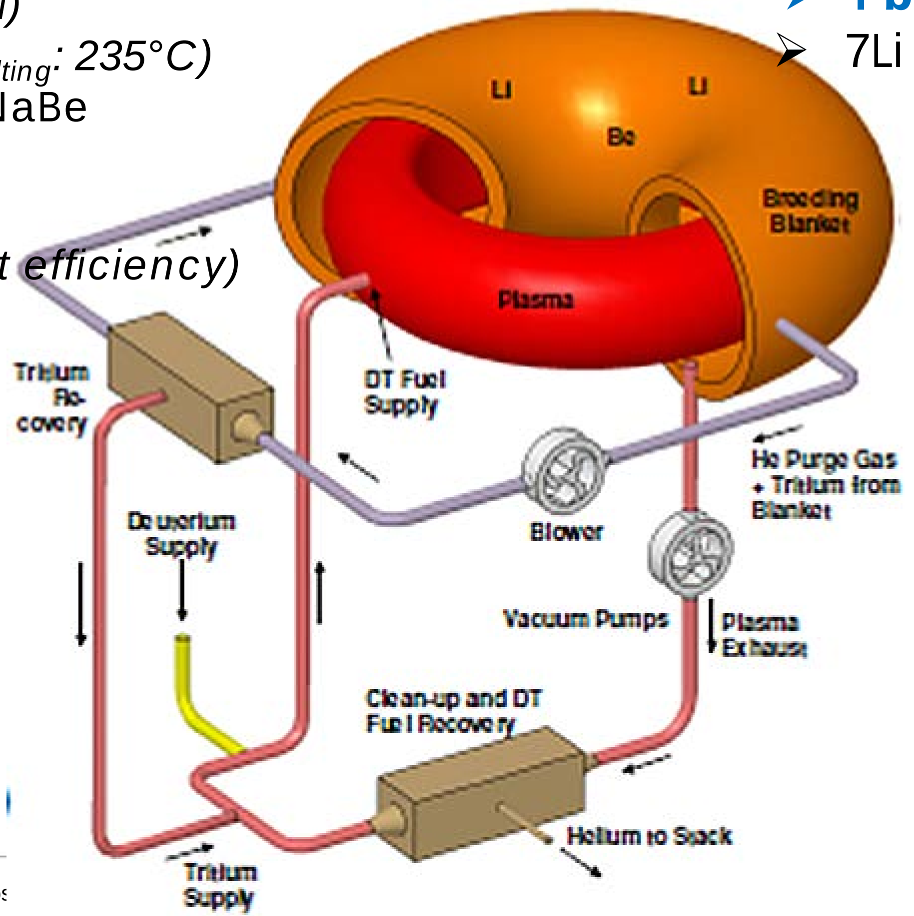
- **Be (n, 2n)**
- **Pb (n, 2n)**
- 7Li (n, n'T)

Main Coolants *(relevant for plant efficiency)*

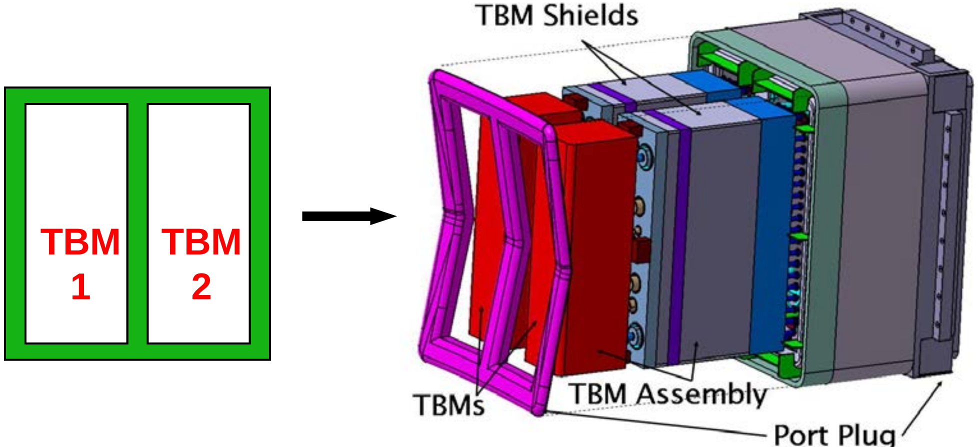
- **Pressurized Water**
- **Helium** (and CO_2)
- Liquid Metals : Li, LiPb-alloy

Main Structural Materials

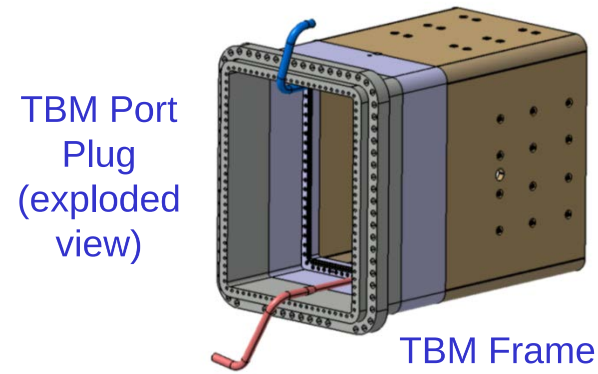
- **Ferritic/Martensitic Steels**
- Vanadium Alloys
- Composites SiC/SiC

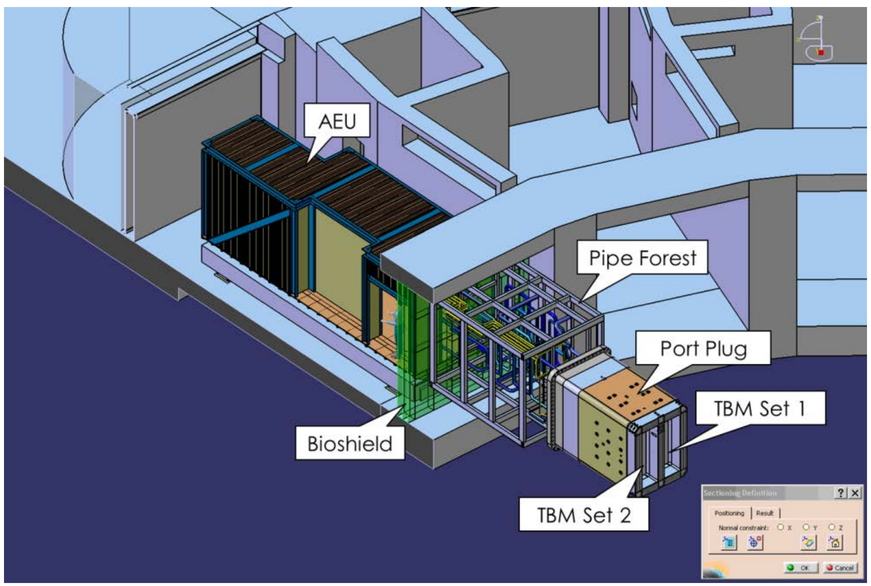


Tritium Breeding Blanket Testing in ITER (1)

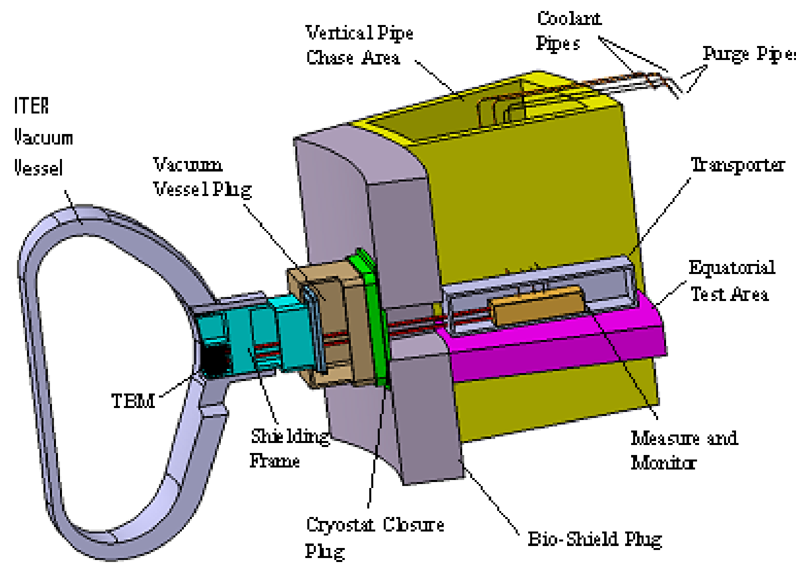


TBM Set





TBM Port arrangement

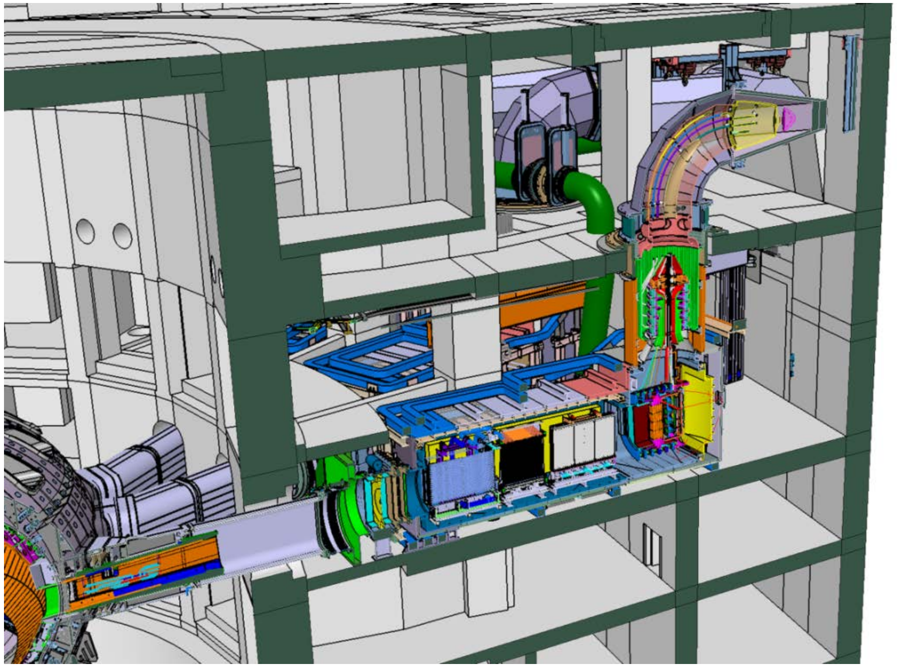


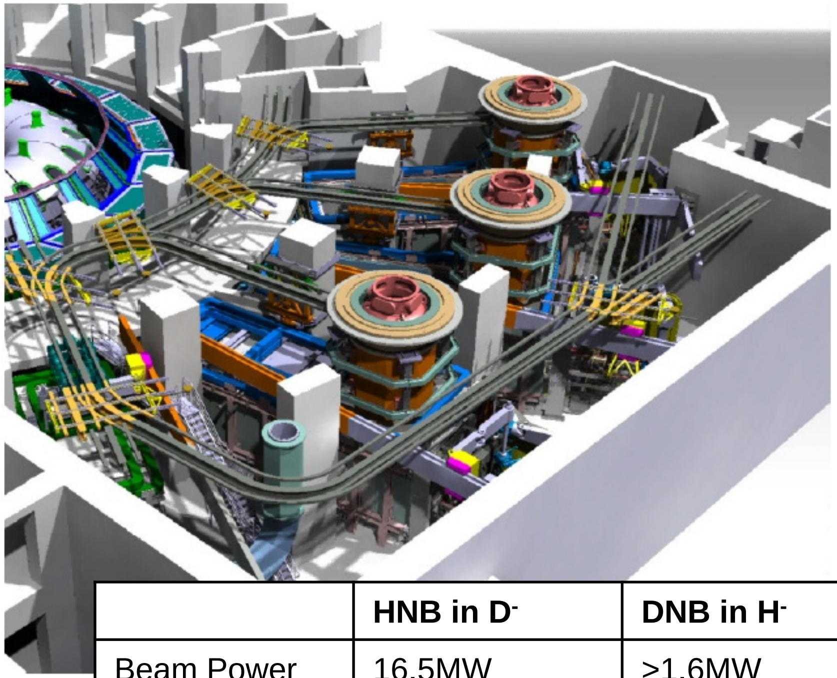
Schematic

Error Field Correction Coils

ITER Neutral Beams (HNB, DNB)

2(+1) Heating Neutral Beam + 1 Diagnostic Neutral Beam





	HNB in D^-	DNB in H^-
Beam Power	16.5MW	>1.6MW
Beam Energy	1MeV	100keV
Current ext. / density	40A / 200A/m^2	60A / 300A/m^2
Divergence	7mrad	<7mrad
Pulse length	3600s	3600s, 1/6 duty cycle
Modulation	2-7Hz (power)	5Hz

Procurement of NB for ITER:

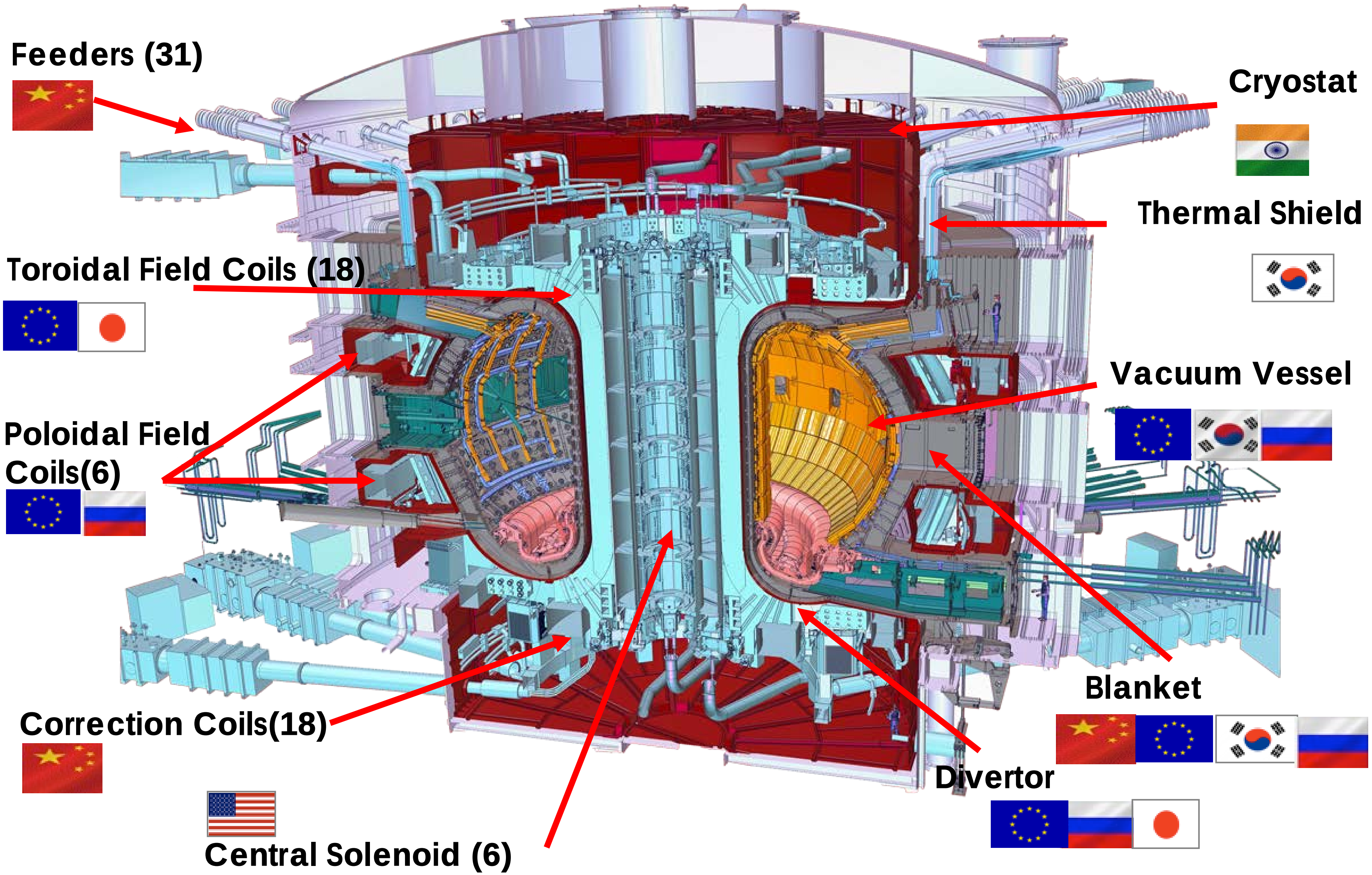
HNB: F4E, JADA

DNB: INDA

Necessary R&D:

NBTF Padua: F4E, JADA, INDA (Ion source, HNB test beds)

INTF: INDA (to reach DNB performance parameters)


Feeders (31)
Cryostat
Thermal Shield
Toroidal Field Coils (18)
Vacuum Vessel
Poloidal Field Coils(6)
Blanket
Correction Coils(18)
Divertor
Central Solenoid (6)