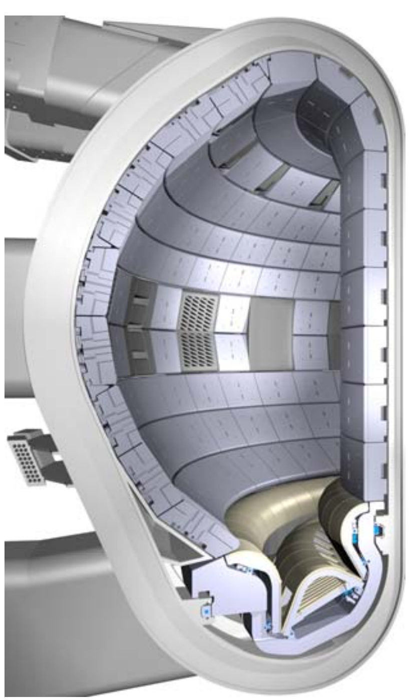
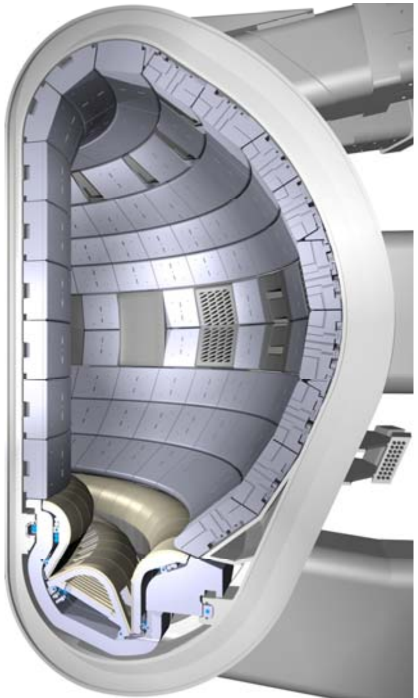
Fusion Energy: Promises Unkept?



Part 2:
ITER

Norbert Holtkamp
ITER Principal Deputy Director General
CERN
Sept 4, 2008



The Way to Fusion Power – The ITER Story

"For the benefit of mankind"

The idea for ITER originated from the Geneva Superpower Summit on November 21,1985, when the Russian Premier Mikhail Gorbachev and the US-President Ronald Reagan proposed that an international project be set up to develop fusion energy "as an essentially inexhaustible source of energy for the benefit of mankind".

The ITER Story II

1988-1991 Conceptual Design Phase

Start of common activities among EU, USSR, USA and Japan. Selection of machine parameters and objectives

1992-1998 Engineering Design Phase

Developed design capable of ignition, but large & expensive

1999-2001

USA withdraws from project

remaining parties search for less ambitious goal

=> New Design (moderate amplification at half the cost)

2003

USA rejoins, China & Korea are accepted as full partners

2005

Cadarache, France, selected as site

India joins the project

2006

Official negotiation, under the auspices of IAEA end in May 2006 with initialing of the official documents in brussels

2007

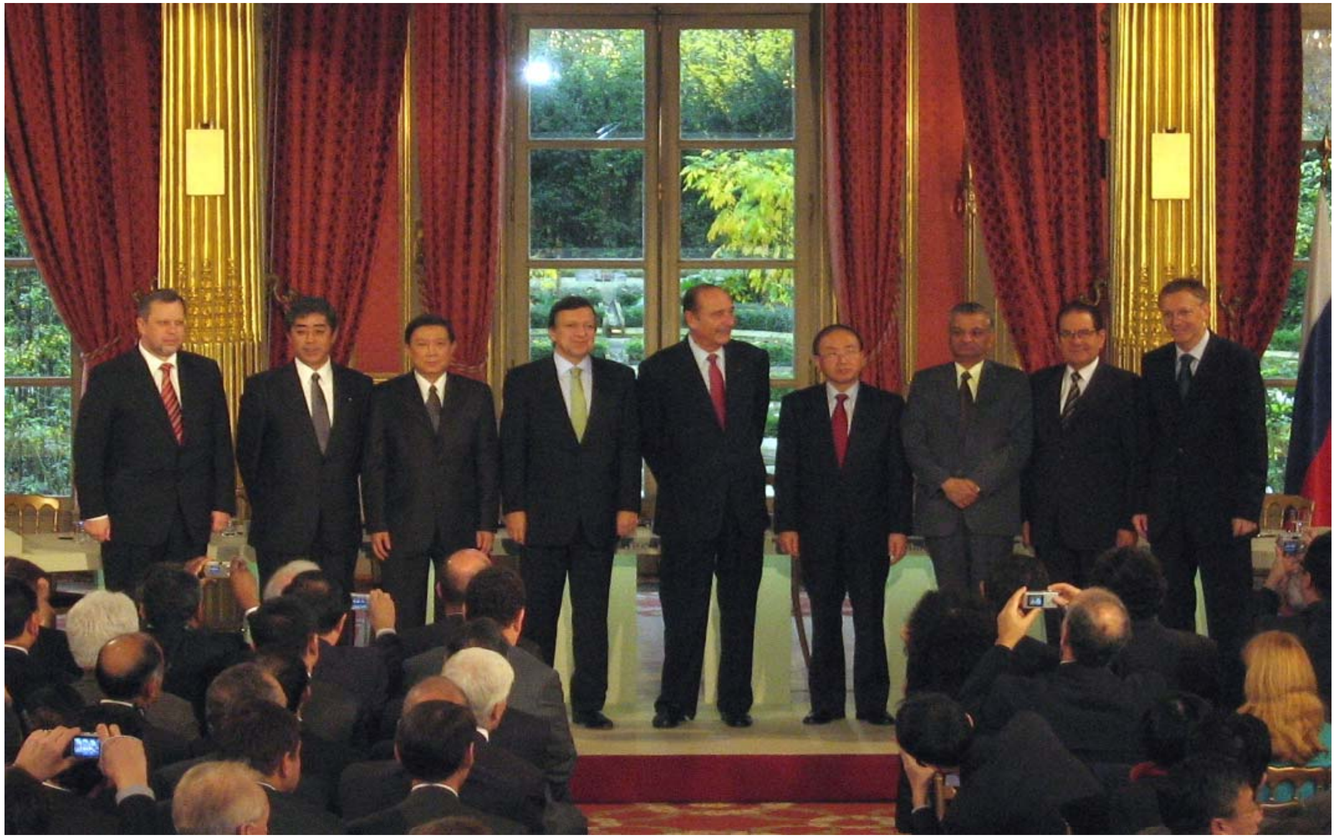
October 24ratification of the Joint ITER Agreement

2008

Kazachstan expresses interest to becom full member. Brazil and Autralia are interested.

The ITER Agreement

On November 21, 2006, the ITER Agreement was signed at the Elysee Palace in Paris by the seven parties China, Europe, India, Japan, Korea, Russian Federation and the United States of America.



„The stakes are considerable, not to say vital for our planet.“
Manuel Barroso, President of the European Commission

ITER leads the way

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

- **The overall programmatic objective:**
  to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

- **The principal goal:**
  to produce a significant fusion power amplification in long-pulse operation (~1000 sec)

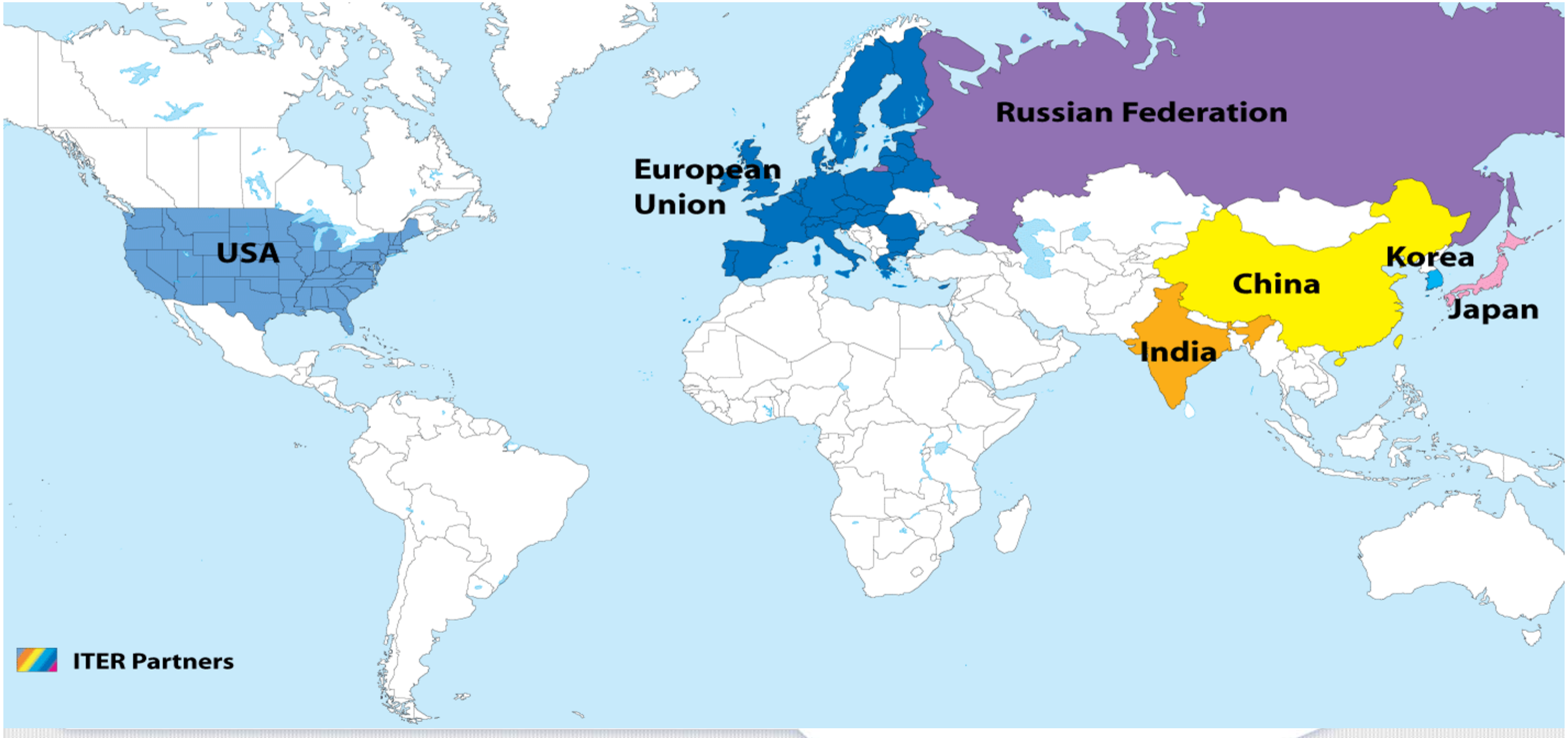
  $$Q \geq 10$$

  input power 50 MW output power 500 MW (fusion power)

- **The execution:**
  ~90% of the contributions are in kind.

ITER - a truly international cooperation…

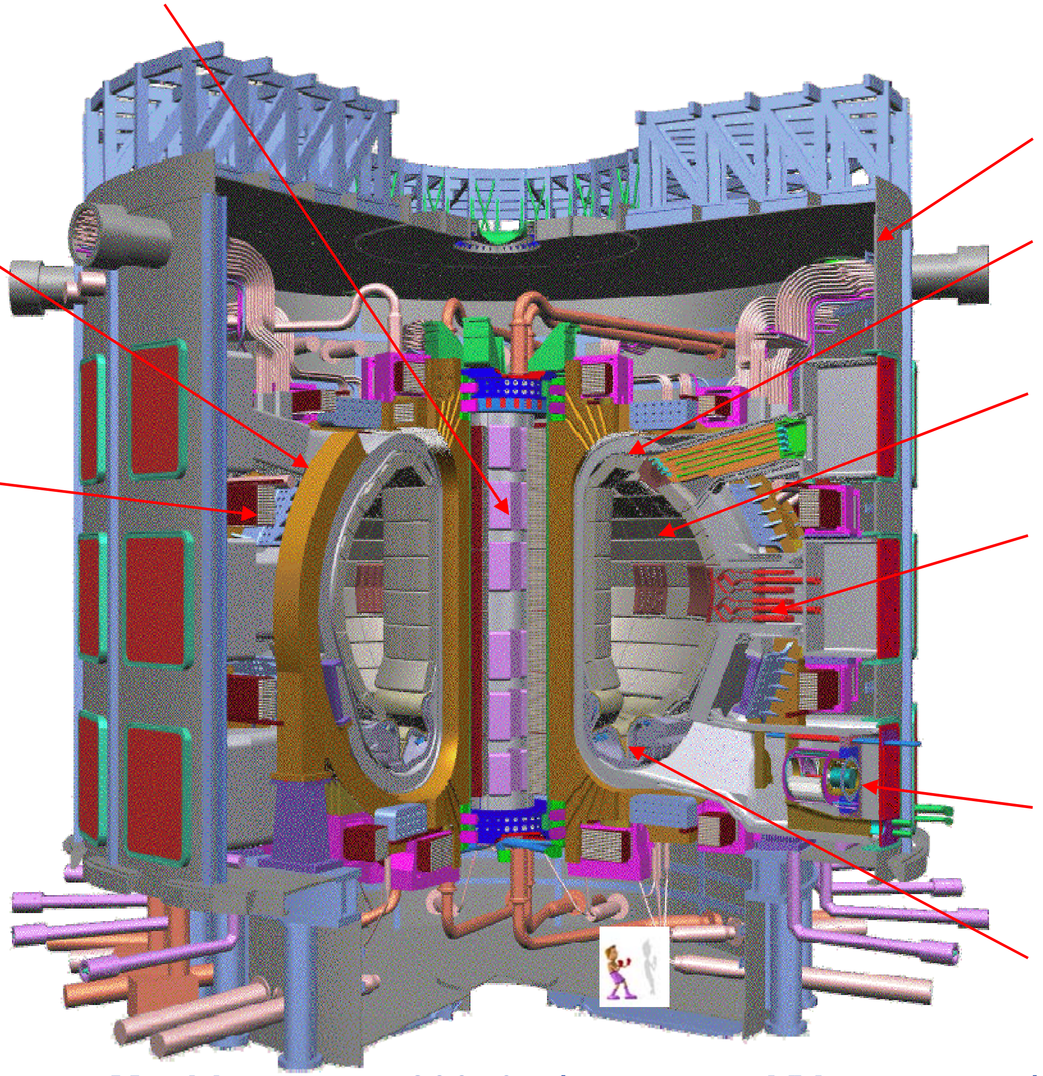
The seven parties involved in the ITER construction represent more than half of the world's population



…based in Cadarache, Southern France

Monaco
Nice
Cadarache
PDDG house
Cannes
Aix-en-Provence
Marseille
Saint-Tropez

The core of ITER



Major plasma radius 6.2 m

Plasma Volume: 840 m^3

Plasma Current: 15 MA

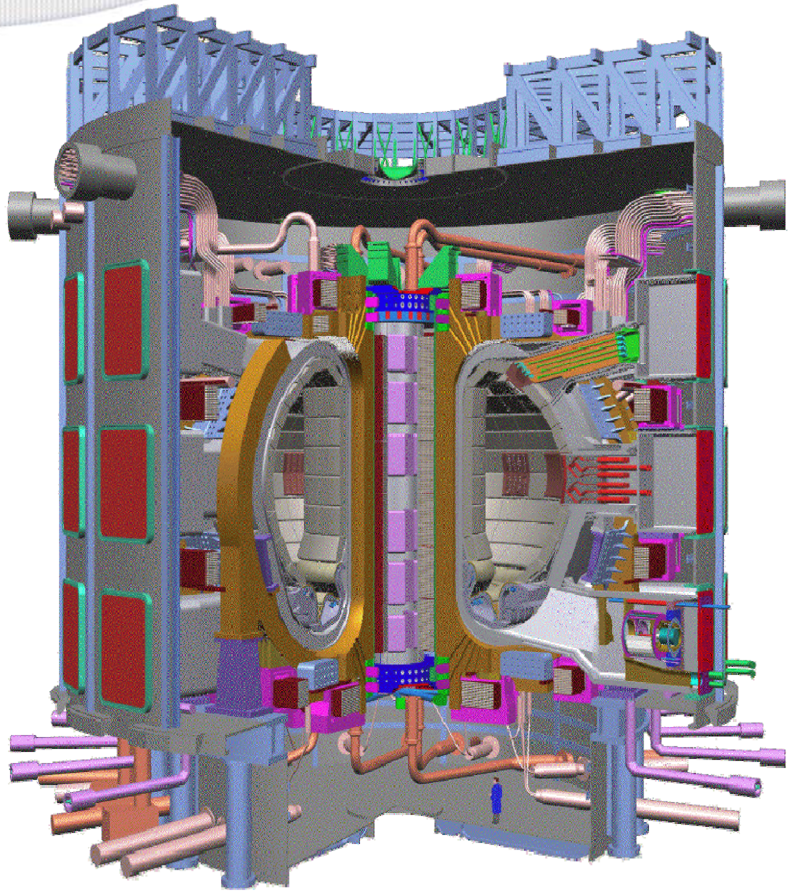
Typical Density: 10^{20} m^{-3}

Typical Temperature: 20 keV

Fusion Power: 500 MW

Machine mass: 23350 t (cryostat + VV + magnets)
- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t

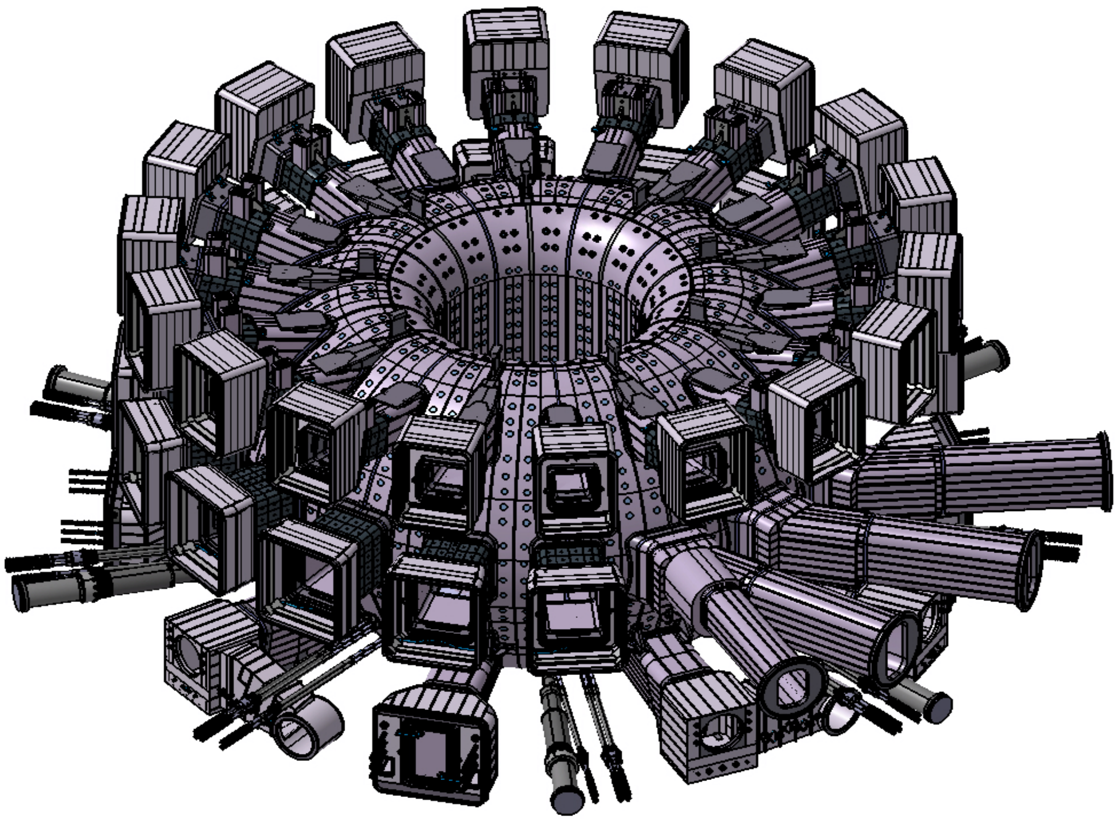
ITER Tokamak – Mass Comparison



Charles de Gaulle mass:
~38000 t (empty)
856 ft (261 m) long
(Commissioned 2001)

ITER Machine mass:
~23000 t
28 m diameter x 29 m tall

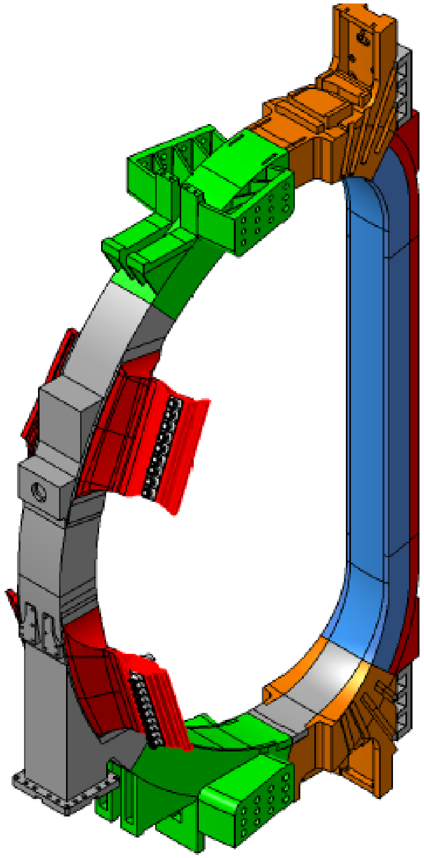
Vacuum Vessel Mass Comparison



VV & In-vessel components mass: ~8000 t
19.4 m outside diameter x 11.3 m tall

Eiffel Tower mass: ~7300 t
324 m tall
(Completed 1889)

TF Coil – Mass Comparison



Mass of (1) TF Coil:

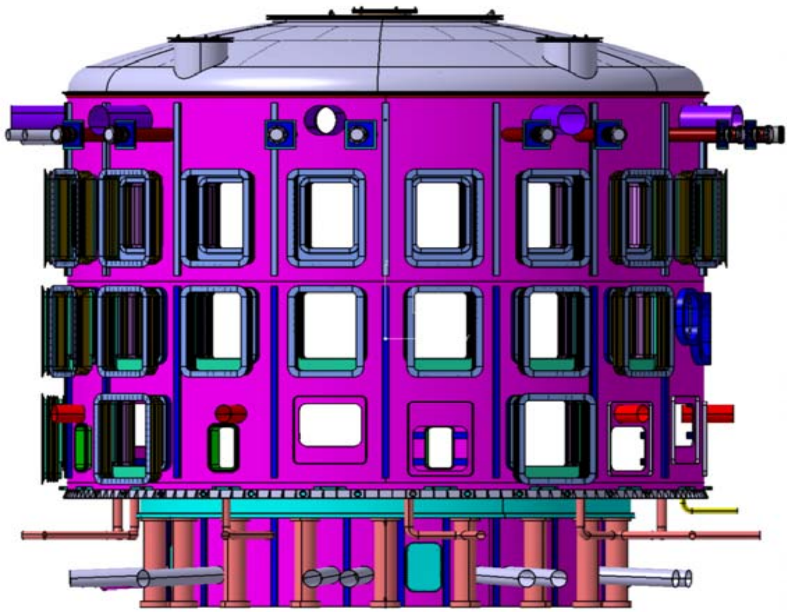
~360 t

16 m Tall x 9 m Wide

D8 Caterpillar Bulldozer

~35 t

Cryostat Size Comparison



ITER Cryostat
~28 m Tall x
29 m Wide

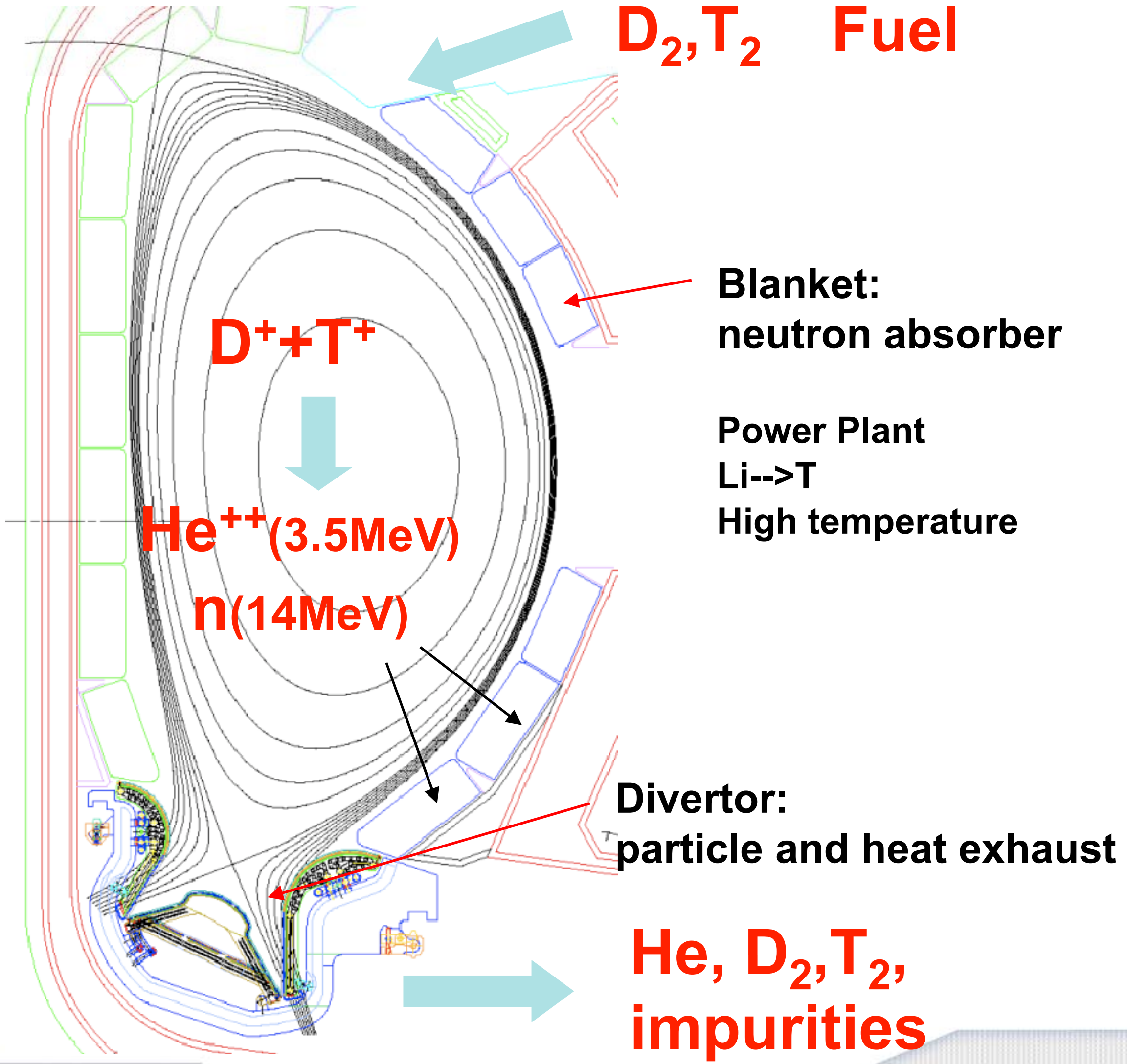
Jefferson Memorial (Washington DC)
~29 m Tall (floor to top of dome)

What determines the scale size of ITER ?

Fusion power production in ITER

ITER Plasma:

R/a:	6.2 m /2 m
Volume:	830 m^3
Plasma Current:	15 MA
Toroidal field:	5.3 T
Density:	10^{20} m^{-3}
Peak Temperature:	2×10^8 ºC
Fusion Power:	500 MW
Plasma Burn	300 - 500 s
(“Steady-state”	~3000 s)



Physics and technology challenges ?
ITER design goals

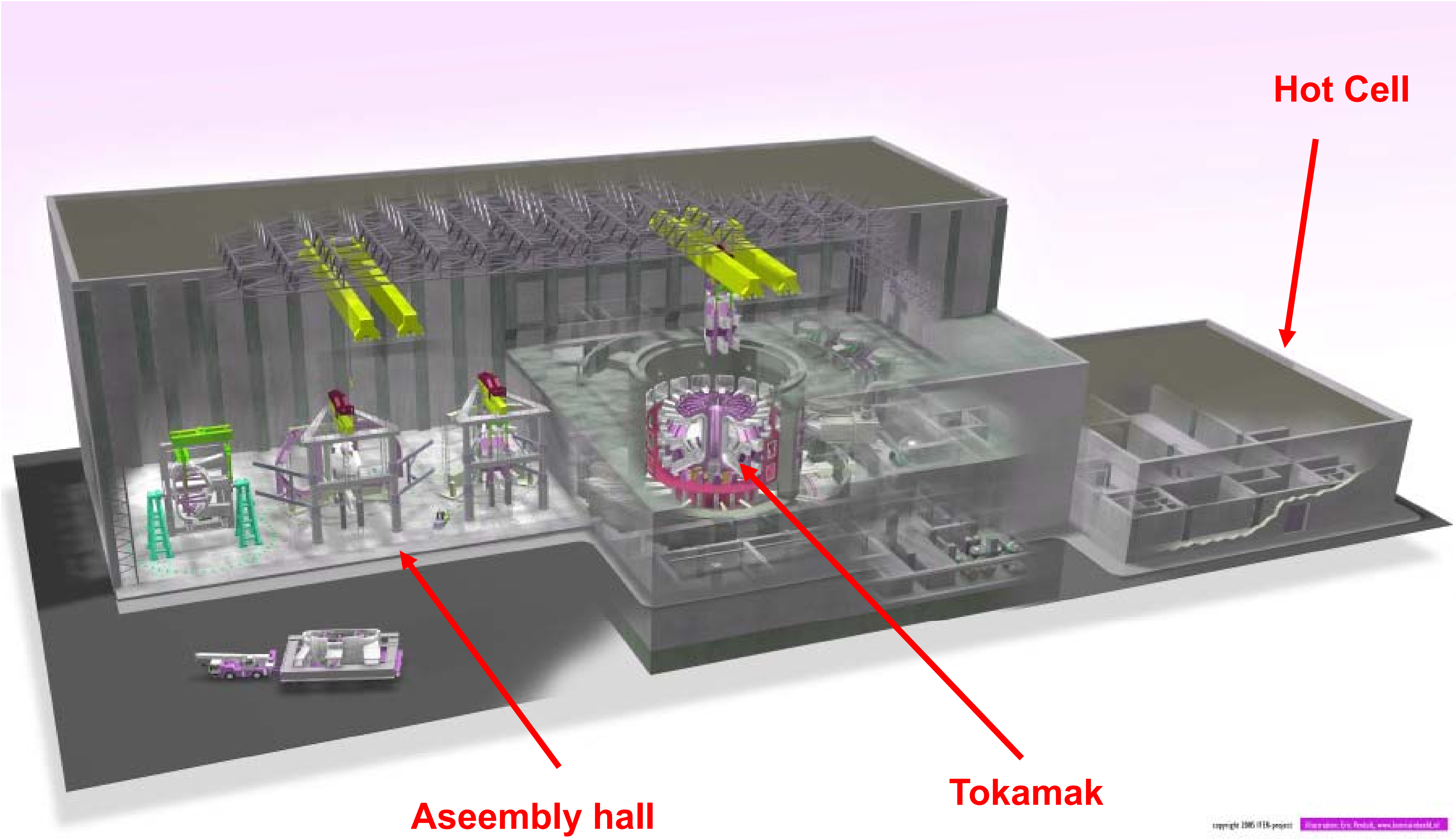
Physics:

- ITER is designed to produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor (Q ≥ 10) in long-pulse operation (300 - 500s)
- aim to achieve steady-state operation of a tokamak (Q = 5)
- retain the possibility of exploring 'controlled ignition' (Q ≥ 30)

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

TOKAMAK Building



Model of the ITER Site

- Will cover an area of about 60 ha
- Large buildings up to 170 m long
- Large number of systems

Preparation for Construction

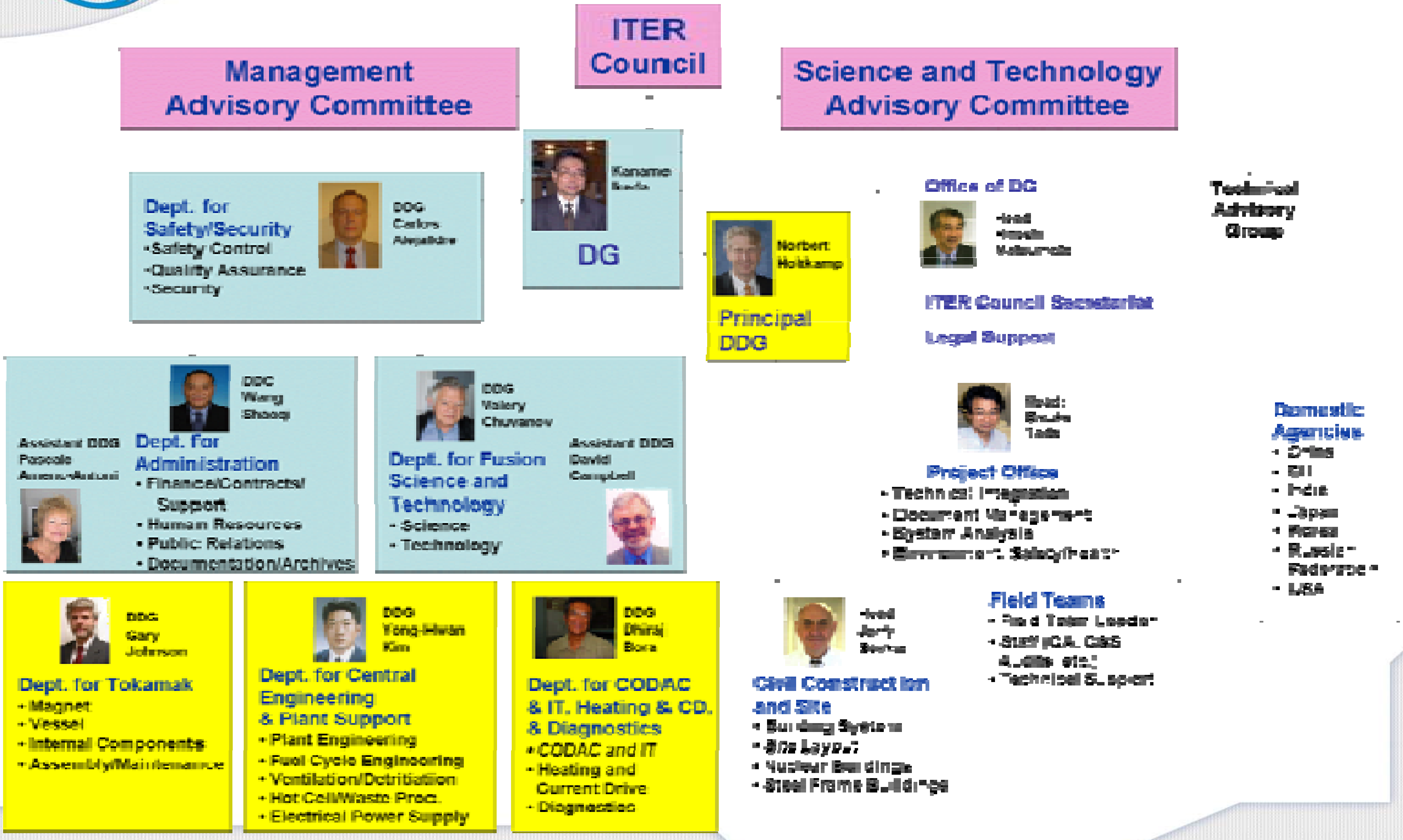
Courtesy AIF

Pictures

Courtesy AIF

The ITER Organization

ITER Organization



The ITER Team in Cadarache

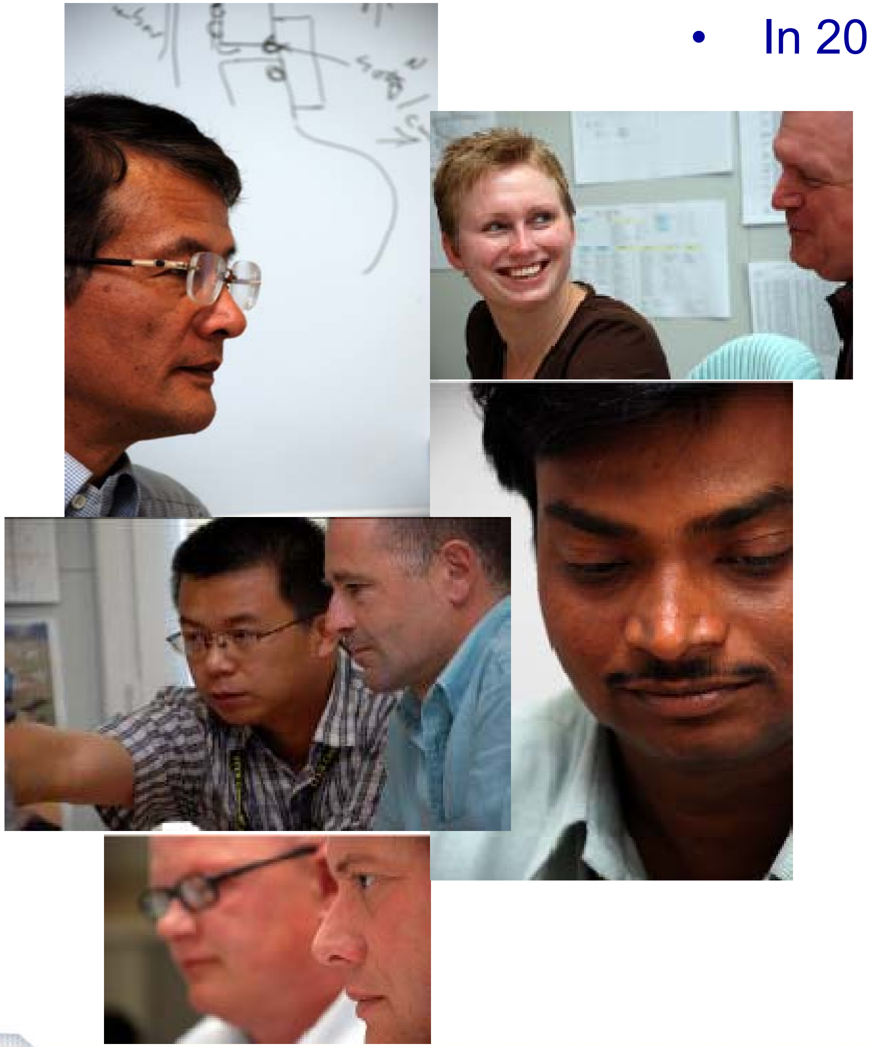
February 2006

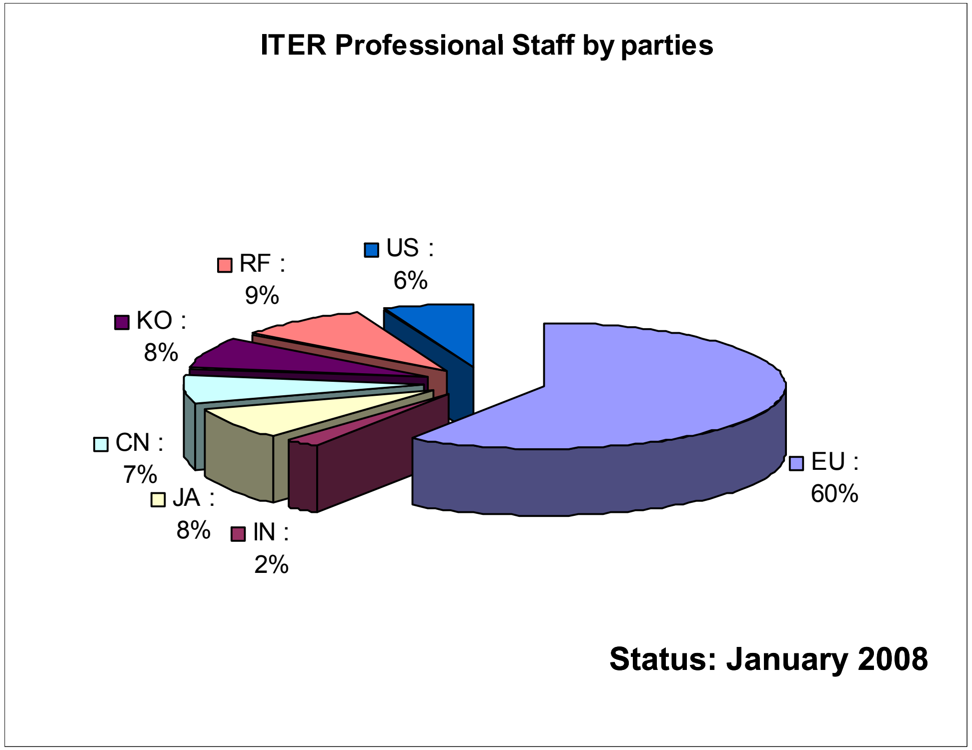
…and 2 years later

February 2008

The ITER Team today

- In June 2008, the IO had a total of 260 staff
- By late 2008, IO should have about 350 staff
- At the end 2010, this should increase to about 600 staff
- In 2016, there will be a total of 700 ITER staff



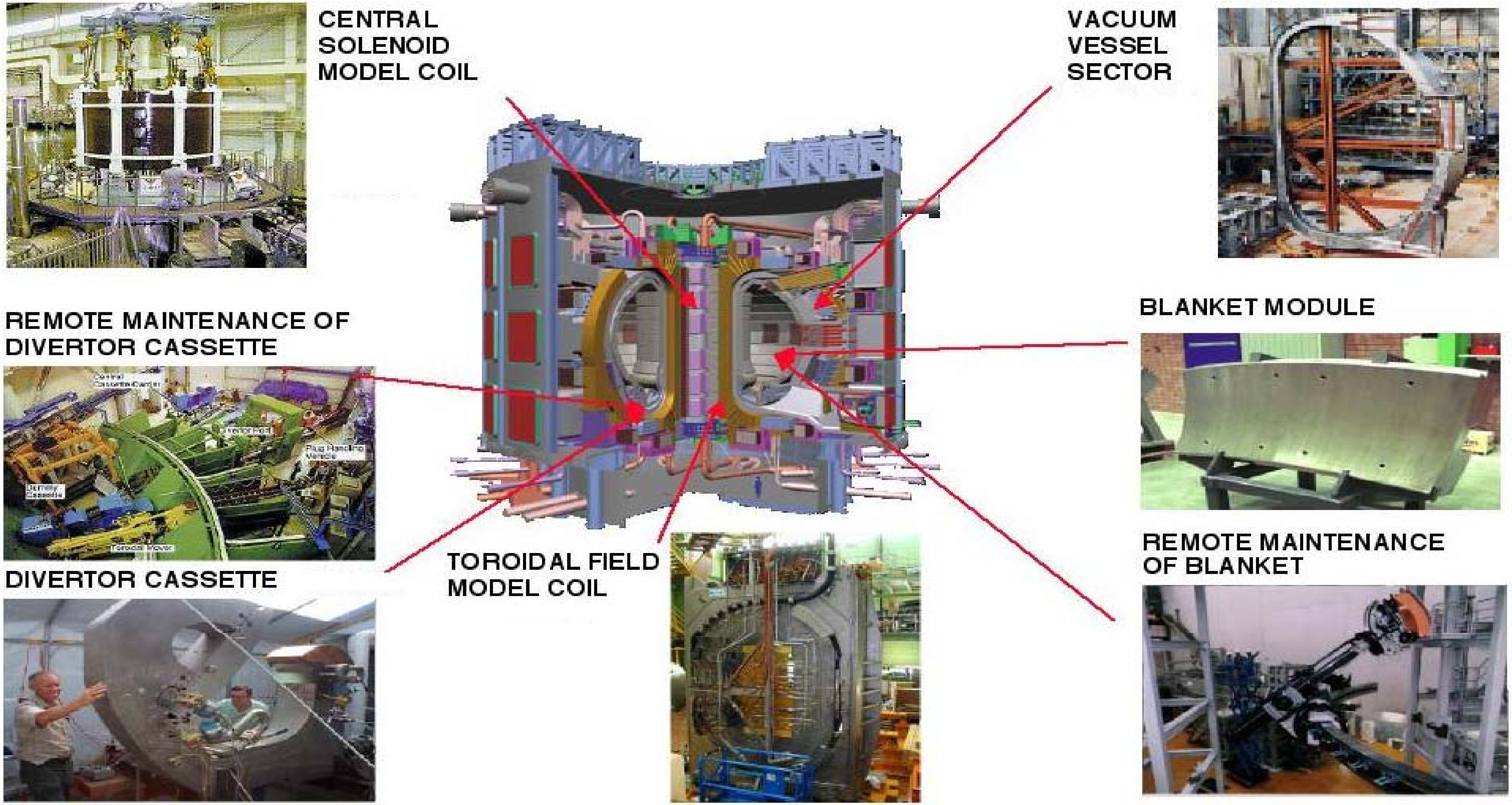


The International Collaboration

The Scope, the Schedule and the Cost of ITER

- Industrial scale Tokamak licensed as a Nuclear Facility
- The Schedule: begin construction in 2007 and have first plasma approximately 10 years later.
- The Construction Cost: 3.578 kIUA (~5.500 M€)
- Reserve: 358 kIUA
- Operations Cost for 25 years: 188 kIUA/year
- Deactivation and Decommissioning: 281 + 530 kIUA

Prior R&D to confirm Constructability

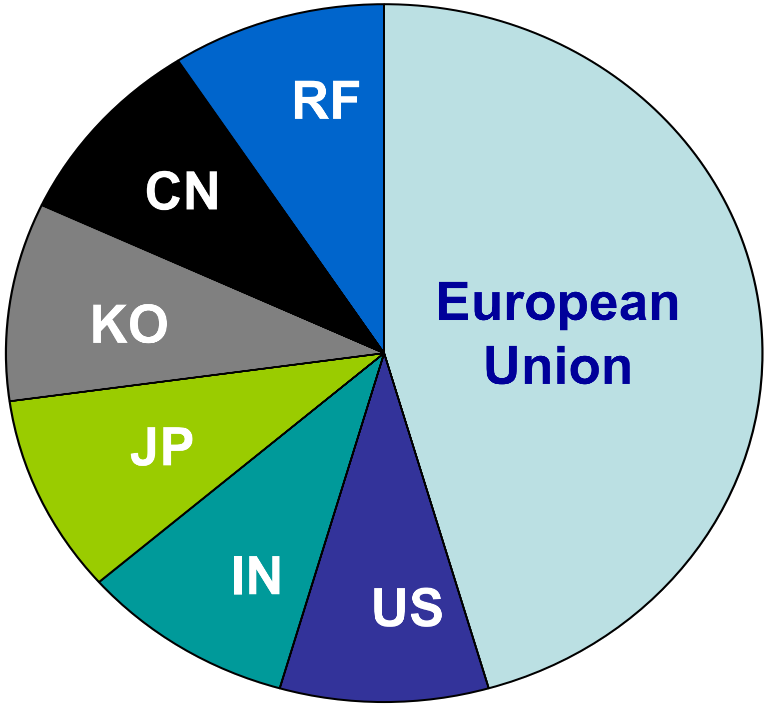


Construction Sharing

How the overall costs are shared:

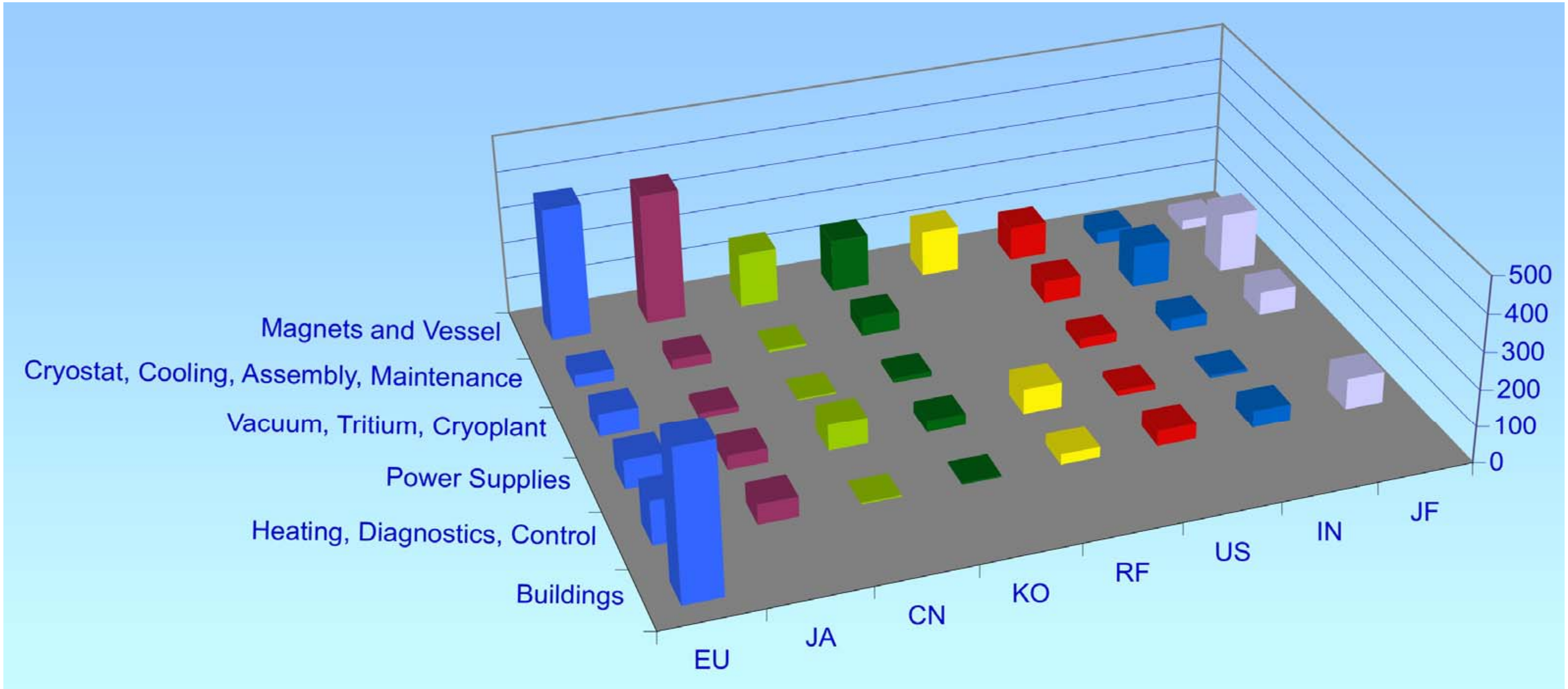
EU 5/11, other six parties 1/11 each. Overall contingency of 10% of total. Total amount: 3577 kIUA (5.365 Mil € / 2008)

Divertor cassette during R&D phase



Procurement Sharing

A unique feature of ITER is that almost all of the machine will be constructed through *in kind* procurement from the Parties



The Design Review: 2001-2007

- 2001 - now (CDA and ITA)
  - End of EDA and start of negotiations on construction and operation
  - 4 site offers: CA, JA, EU 1+2.
- After finishing the 2001 baseline, technical work continued while the negotiations were ongoing based on 2001 cost with no official body in place to validate any changes or cost adaptations.
- Two phases:
  - 2001-2006 changes that were integrated without detailed "value" study.
    - All of them are integrated in the design.
  - Design Review executed with ~200 people worldwide.
    - Improvements to the design increase of operational space

The Request from the Science & Technology Community

1	*Vertical Stability*
2	*Shape Control / Poloidal Field Coils*
3	*Flux Swing in Ohmic Operation and CS*
4	*ELM Control*
5	*Remote Handling*
6	*Blanket Manifold Remote Handling*
7	*Divertor Armour Strategy*
8	*Capacity of 17 MA Discharge*
9	*Cold Coil Test*
10	*Vacuum Vessel / Blanket Loading Condition Test*
11	*Blanket Modules Strategy*
12	*Hot Cell Design*
13	*Heating Current Drive Strategy, Diagnostics and Research Plan*

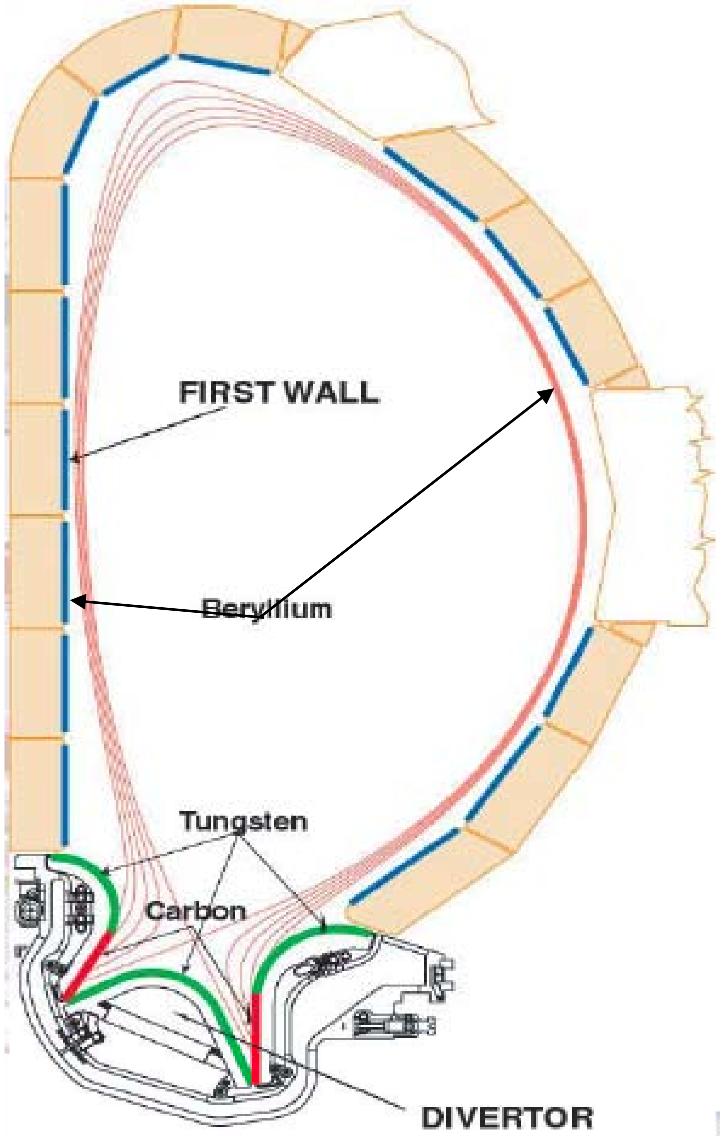
- Technical Feasibility
- Necessity to do now
- Cost and Schedule Impact
- Ability to fund

Plasma Transients

- Several types of transient event can occur in plasmas, only some of which need to be controlled:
  - Sawteeth:
    - a repetitive mhd instability which modulates central plasma parameters (principally benign)
  - Edge localized modes (ELMs):
    - a repetitive mhd instability which modulates edge plasma parameters (principal impact on lifetime of plasma facing components)
  - MARFEs:
    - a radiation instability which can lead to localized heating of the first wall (first wall designed to handle estimated heat loads)
  - Disruptions:
    - mhd instabilities trigger a rapid termination of plasma energy and current (can produce enhanced erosion of PFCs; generates eddy current forces in structures)
  - Vertical Displacement Events (VDEs):
    - loss of plasma vertical position control causes loss of energy and current (can produce localized surface melting/ ablation of PFCs; generates eddy and halo current forces in structures)

Plasma Facing Components - Challenges

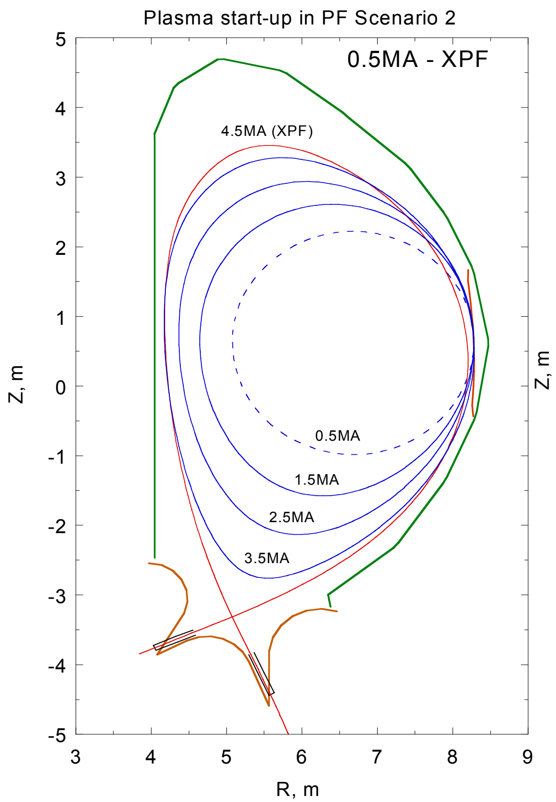
- CFC divertor targets (~50m^2):
  - erosion lifetime (ELMs!) and tritium codeposition
  - dust production
- Be first wall (~700m^2):
  - dust production and hydrogen production in off-normal events
  - melting during VDEs
- W-clad divertor elements (~100m^2):
  - melt layer loss at ELMs and disruptions
  - W dust production - radiological hazard in by-pass event

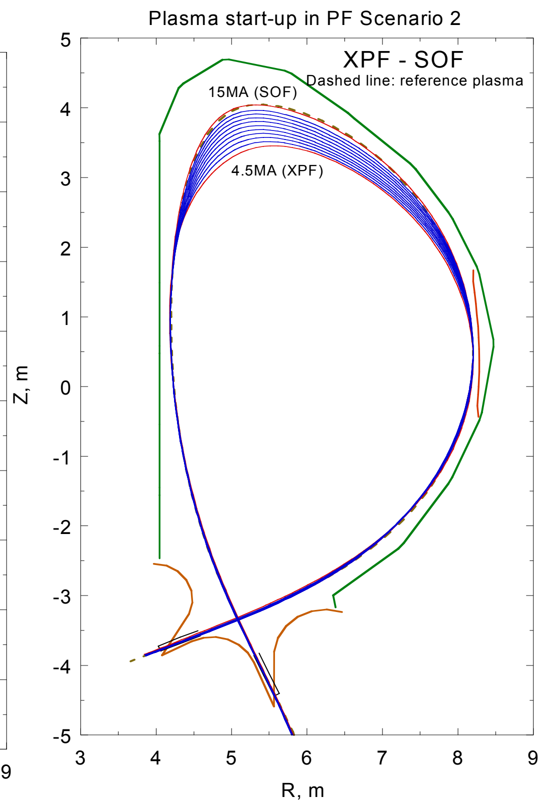


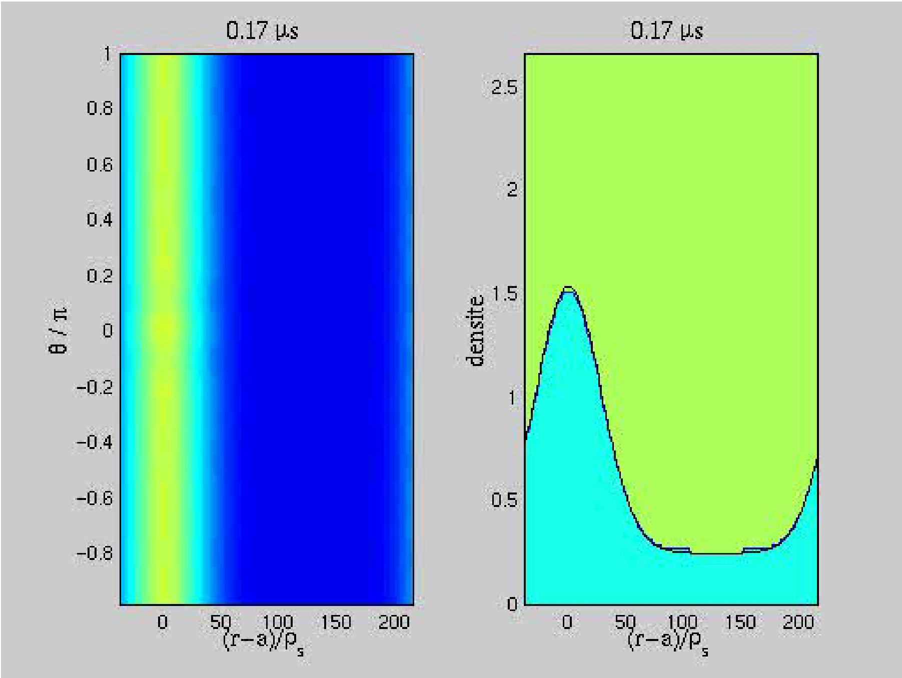
An ITER Plasma

A Q=10 scenario with:

I_p=15MA, P_{aux}=40MW, $H_{98(y,2)}$=1

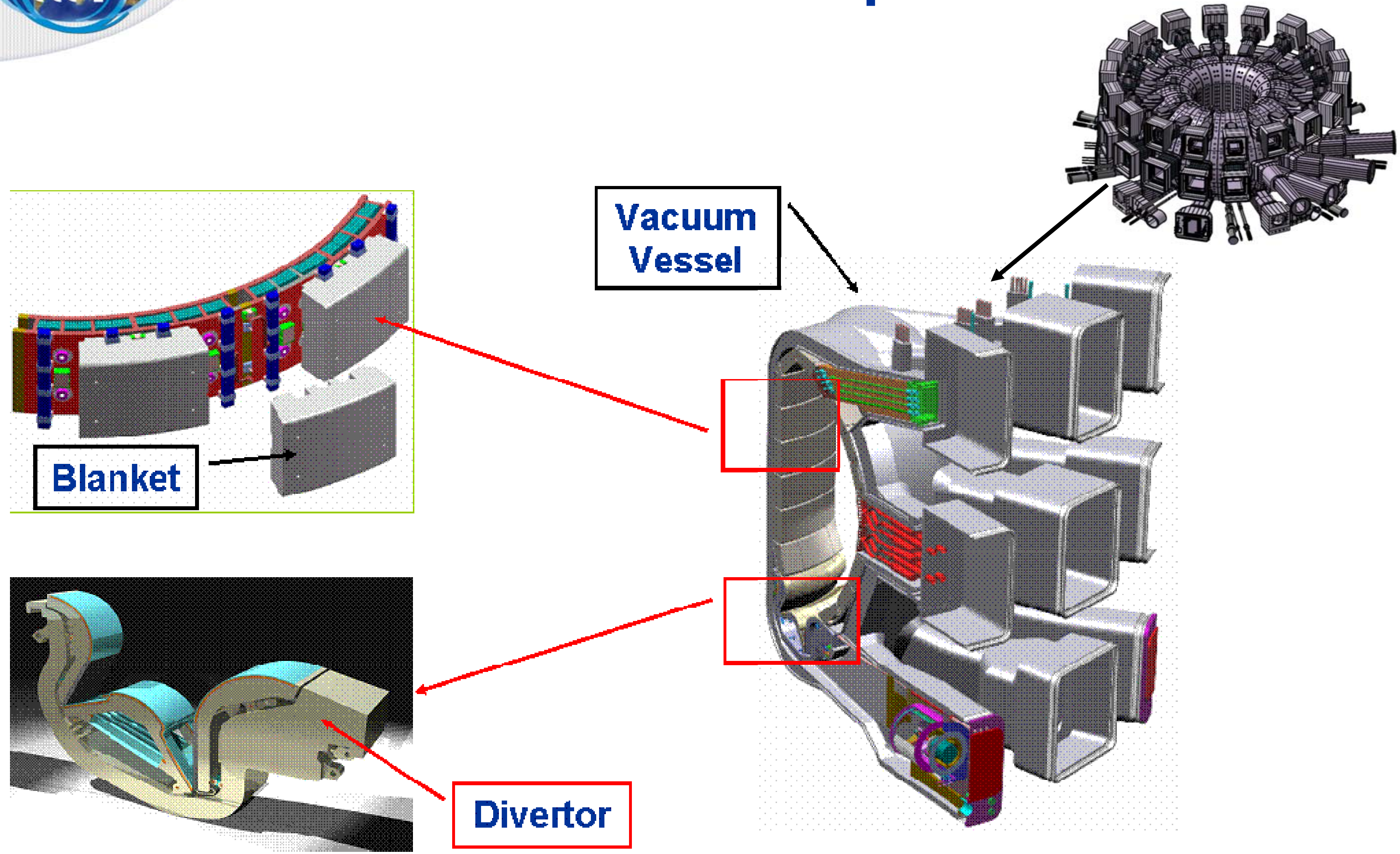




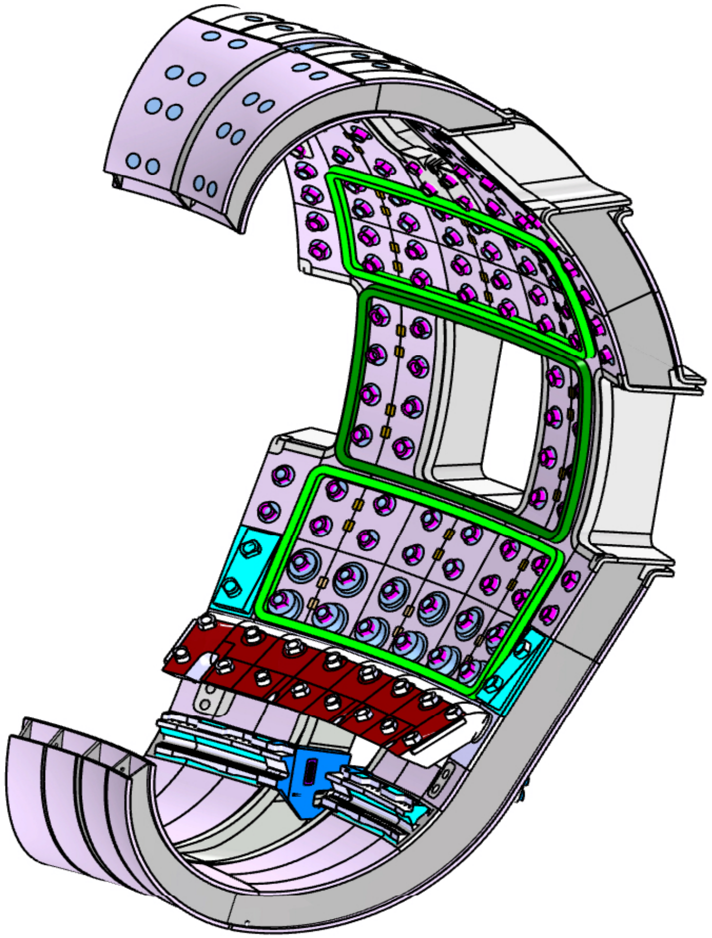


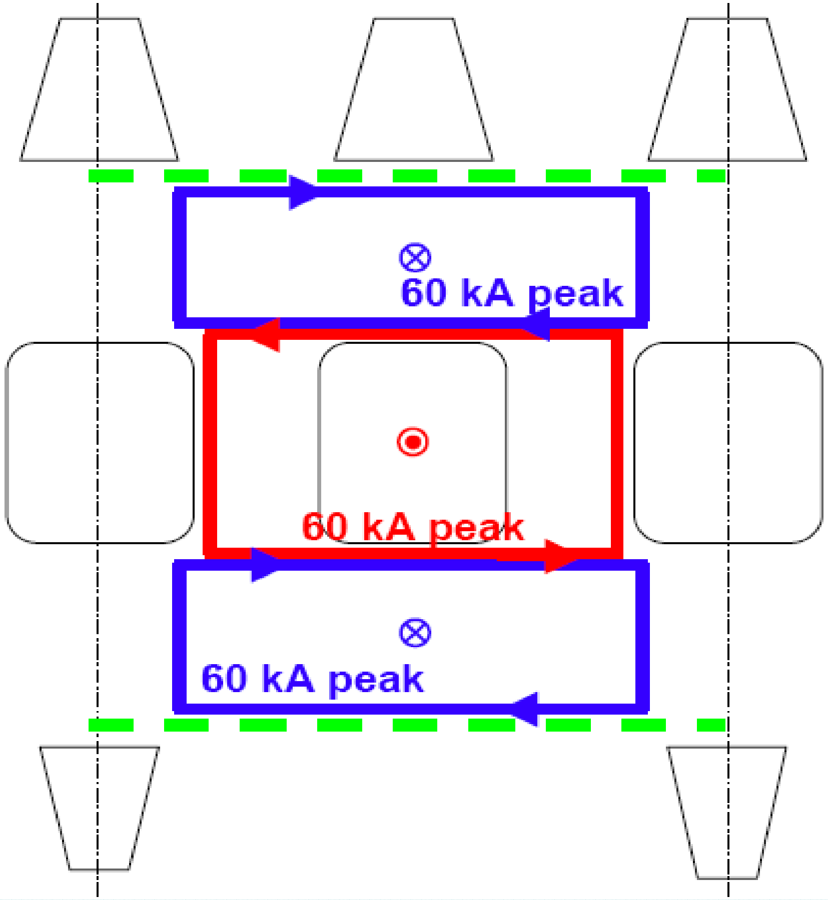
Current Ramp-up Phase

VV and In-vessel Components



ELM Control by RMP Coils in ITER

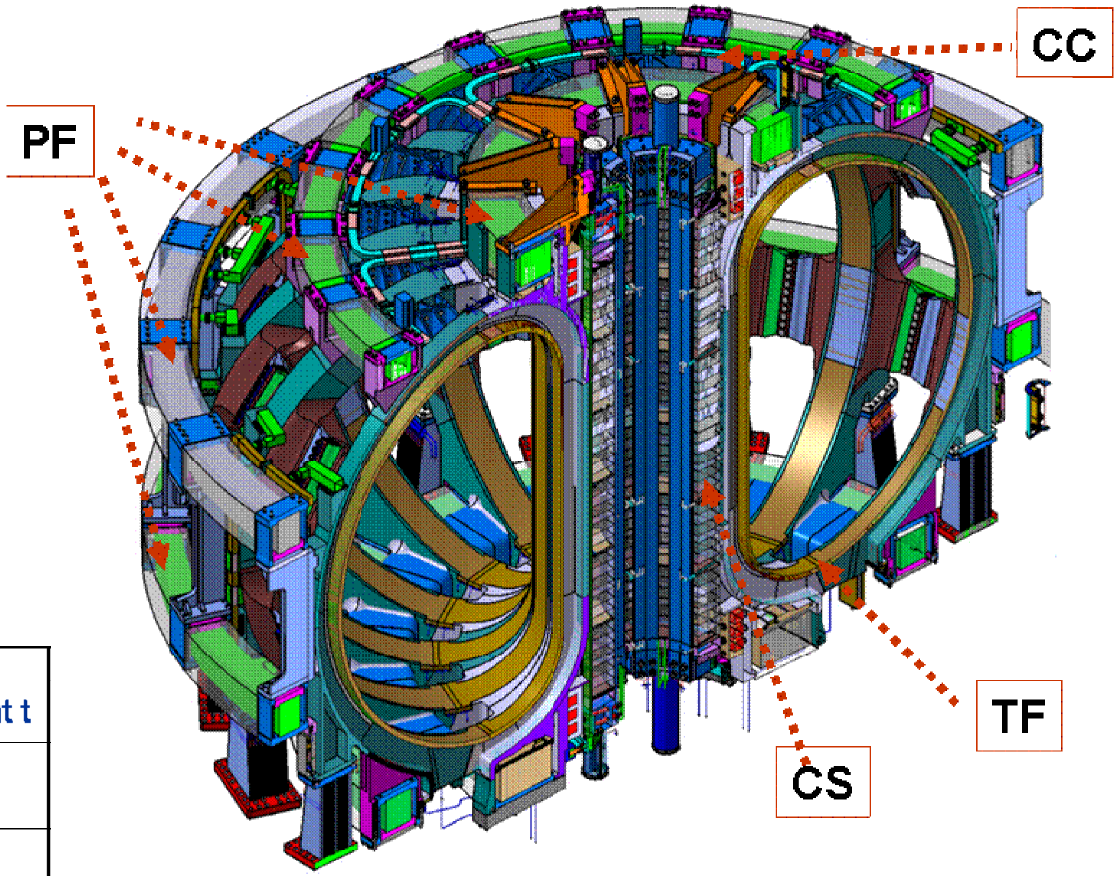




- A set of resonant magnetic perturbation (RMP) coils under design:
  - would consist of 9 toroidal x 3 poloidal array on internal vessel wall

Overview of the Magnet System

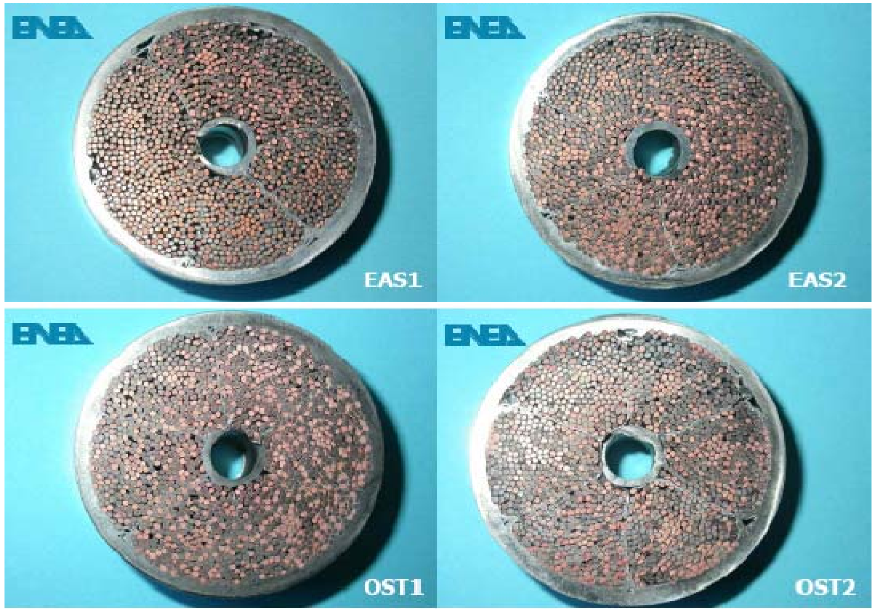
- 48 superconducting coils
  - 18 TF coils
  - 6 CS modules
  - 6 PF coils
  - 9 pairs of CC



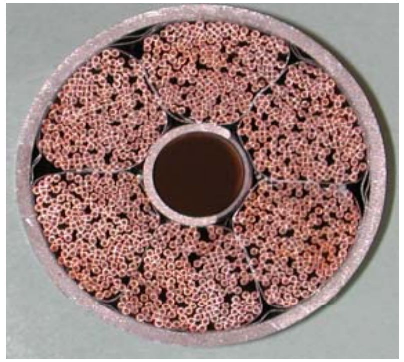
System	Energy GJ	Peak Field	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

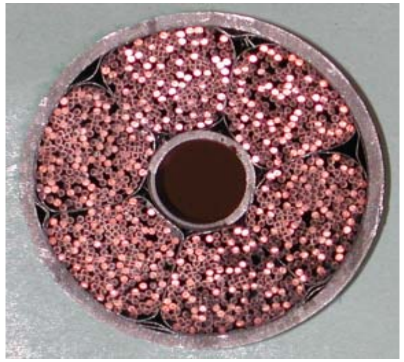
Magnet Conductor

- Ongoing field-cycling stress tests showing very promising results



- cables tested in 2006 showed substantial degradation

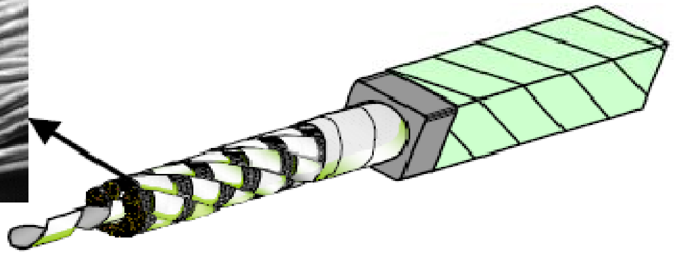


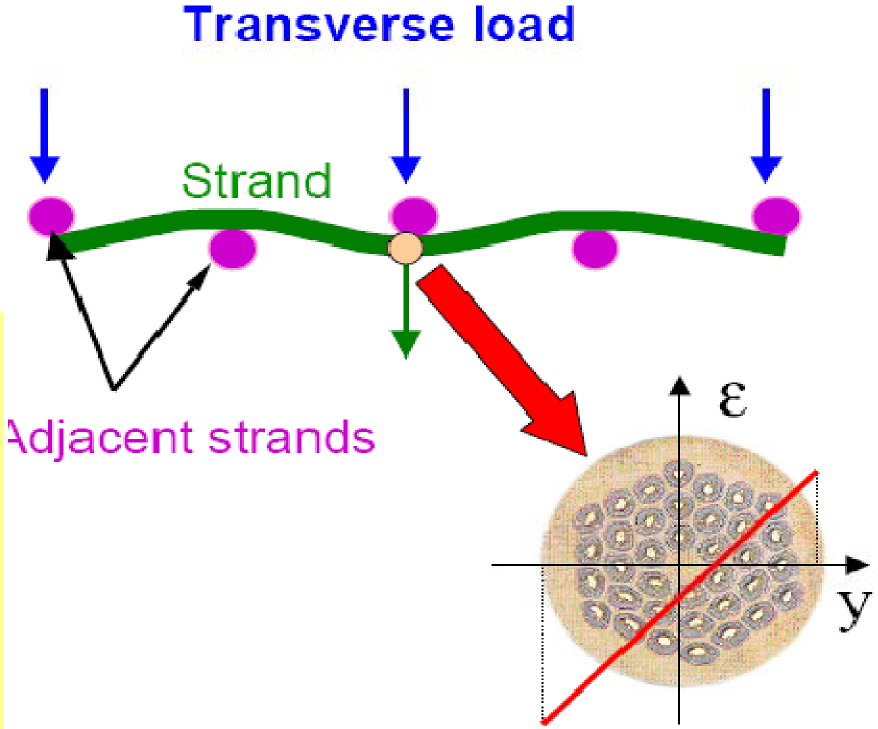


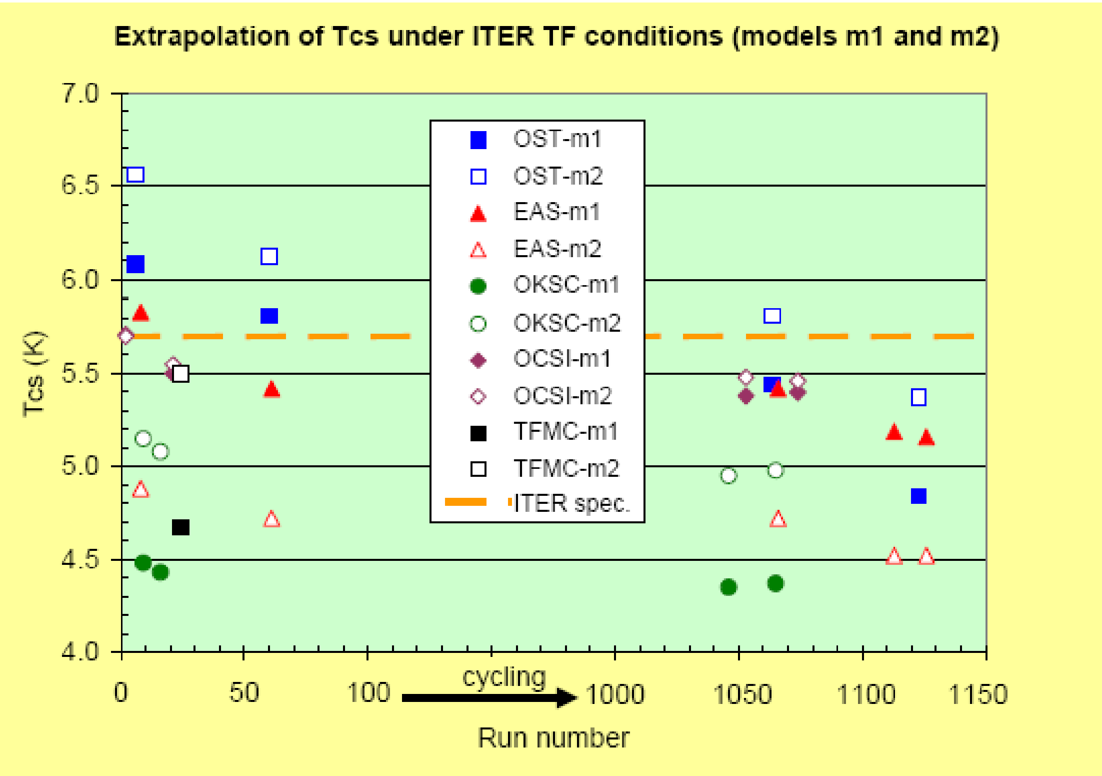
4 out of the 6 producers for TF cable have qualified cables now!

Performance Degradation in High Field Magnets

Courtesy: D. Ciazyinski
Workshop on CICC, Aix –Jan15-17

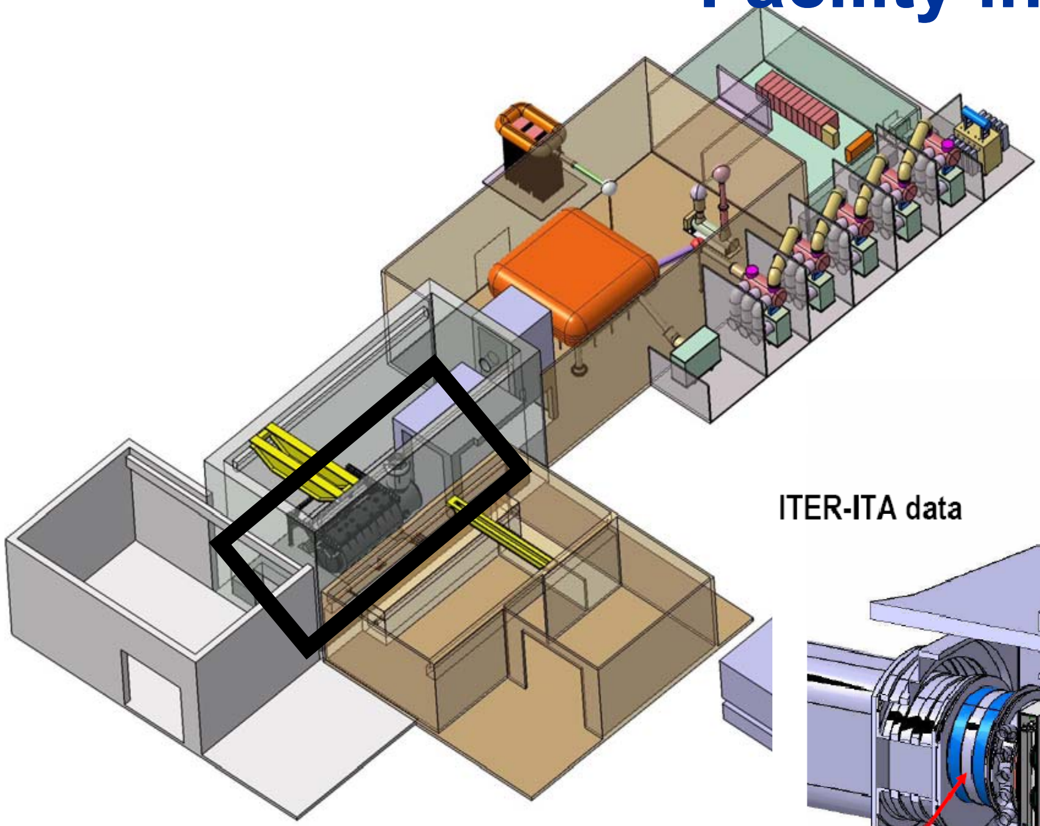






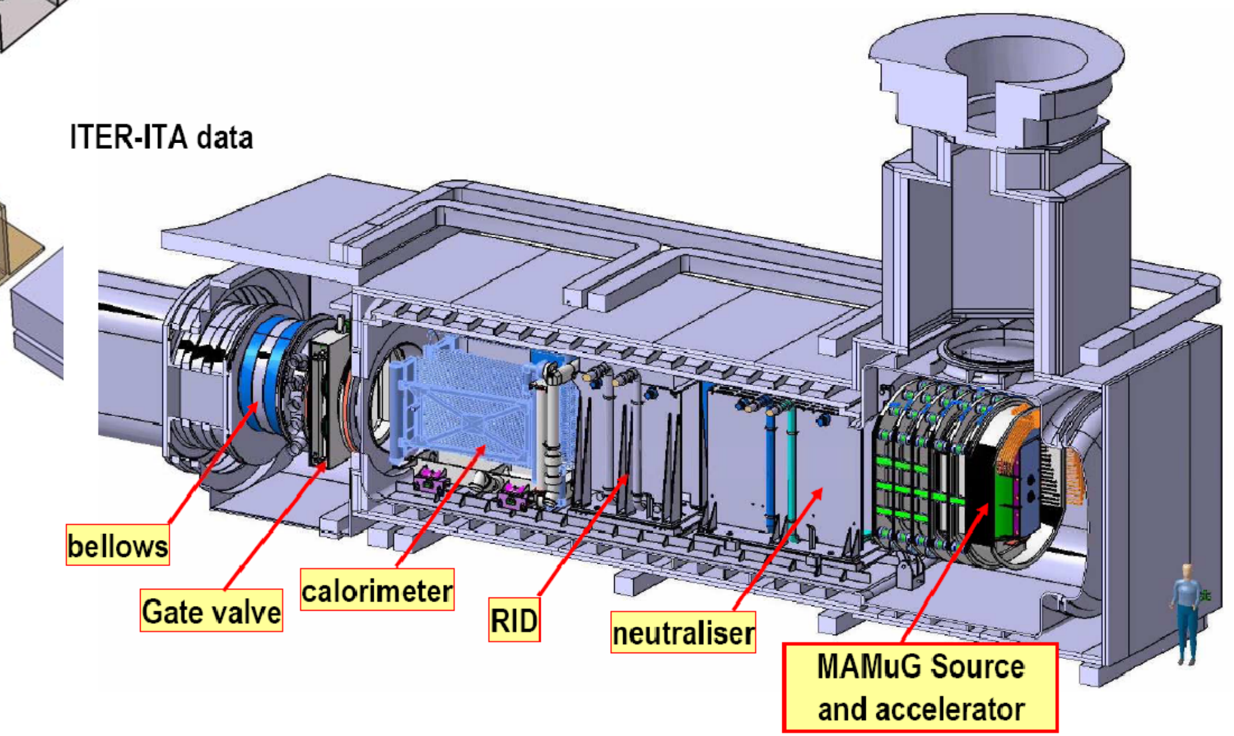
Lay Out Of The Neutral Beam Test Facility in Padua

ITER NB Heating System
1 MV DC
~40 A of H^- current
20 MW delivered to Plasma
Up to 3 systems on ITER

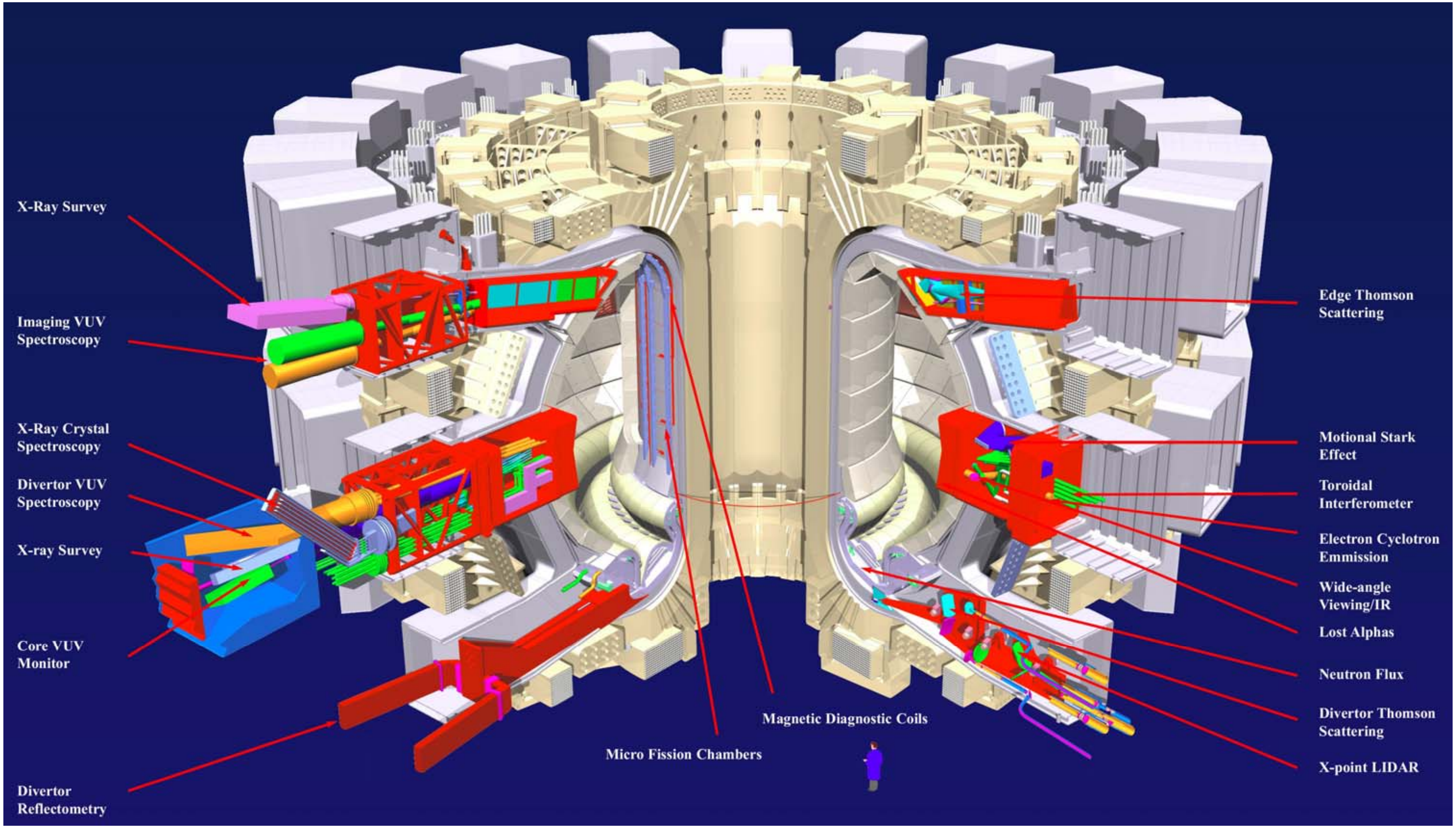


Neutral Beam Test Facility

ITER-ITA data

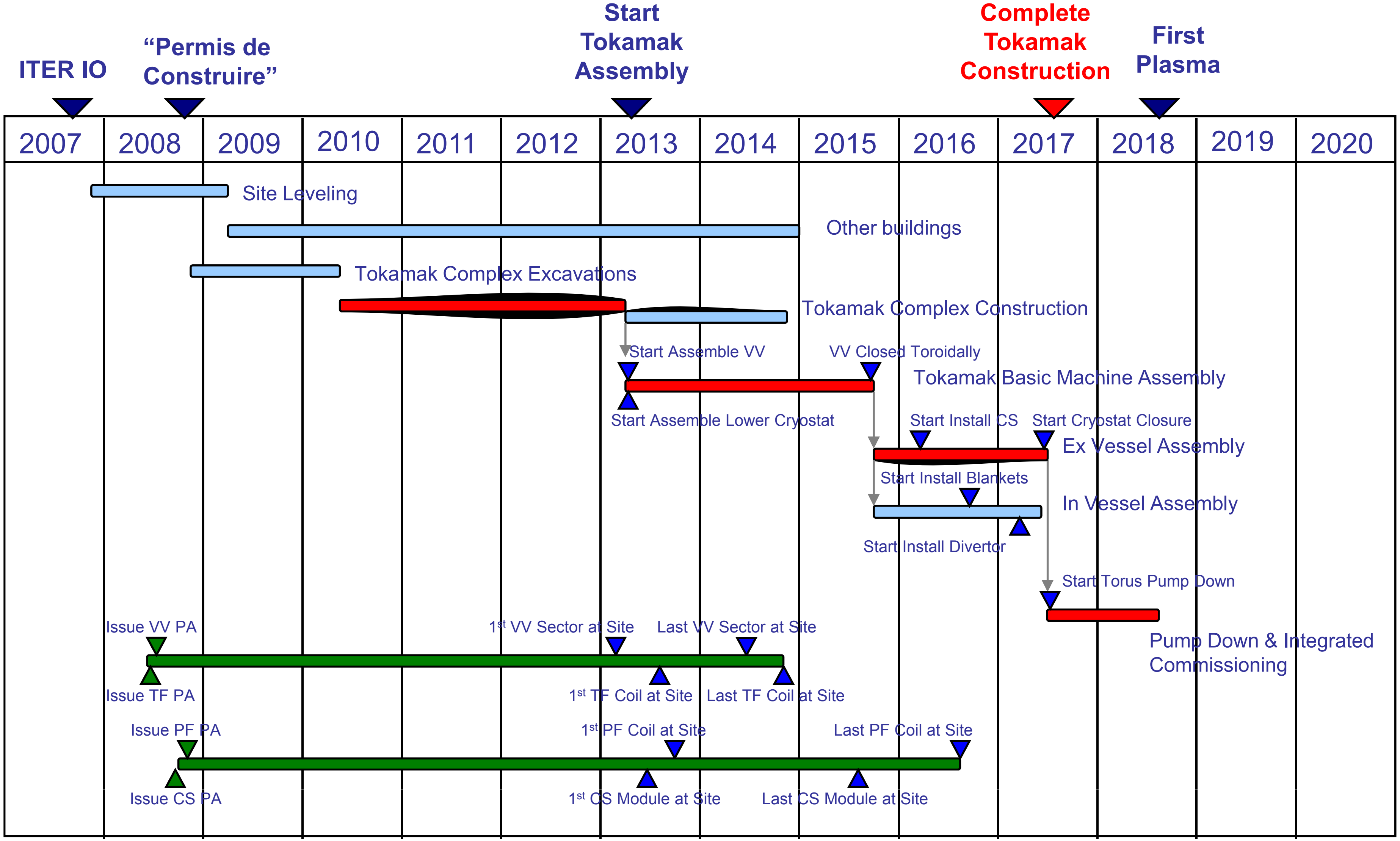


Diagnostics



Resulting Reference IPS

31 March 2008



Procurement Sharing Principle
@ ITER …

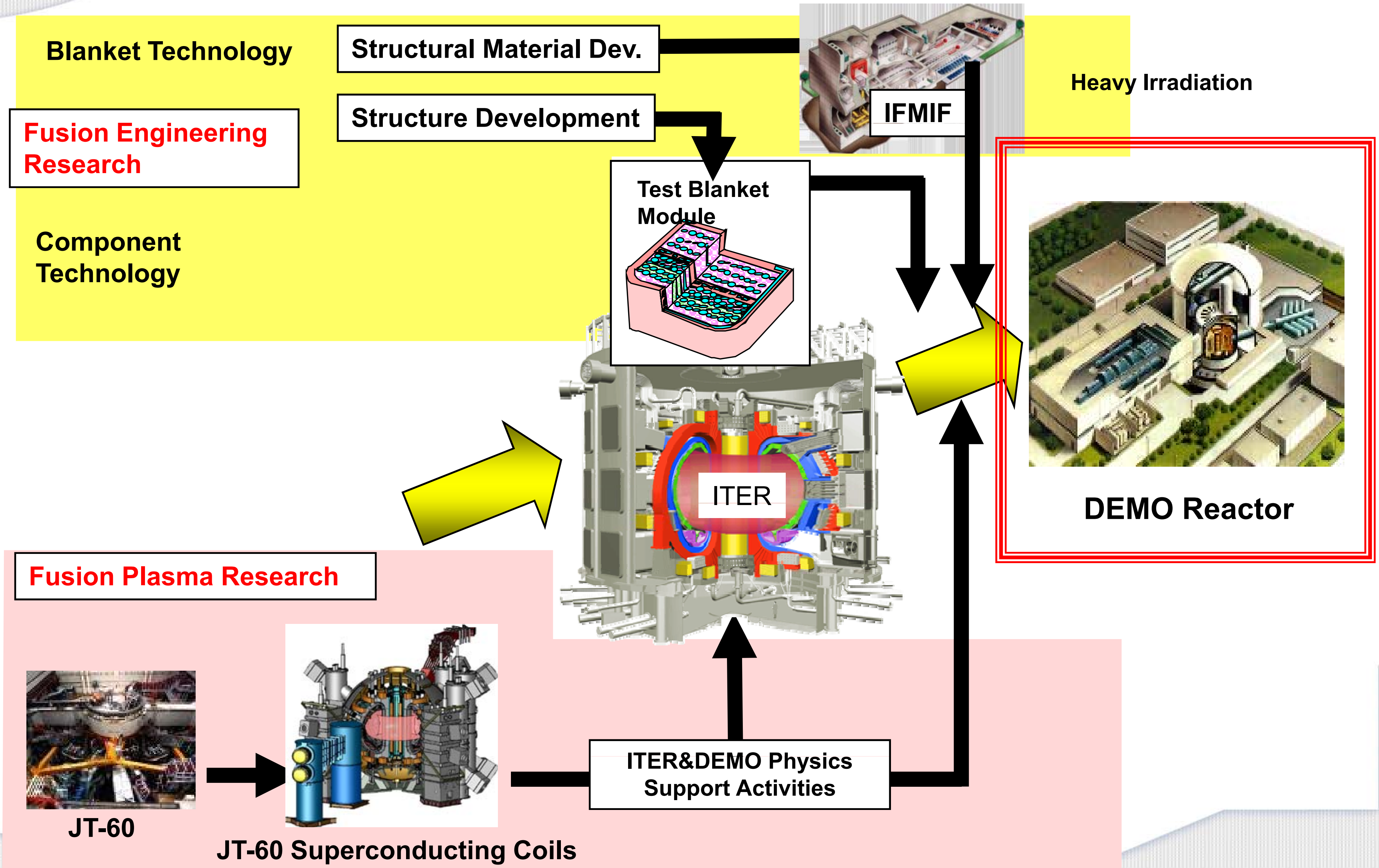
… is based on distributing knowledge by split procurements

…is technological / industrial capability shared amongst Members

…is certainly not the cheapest way to build

…is definitely an acceleration through distributed production

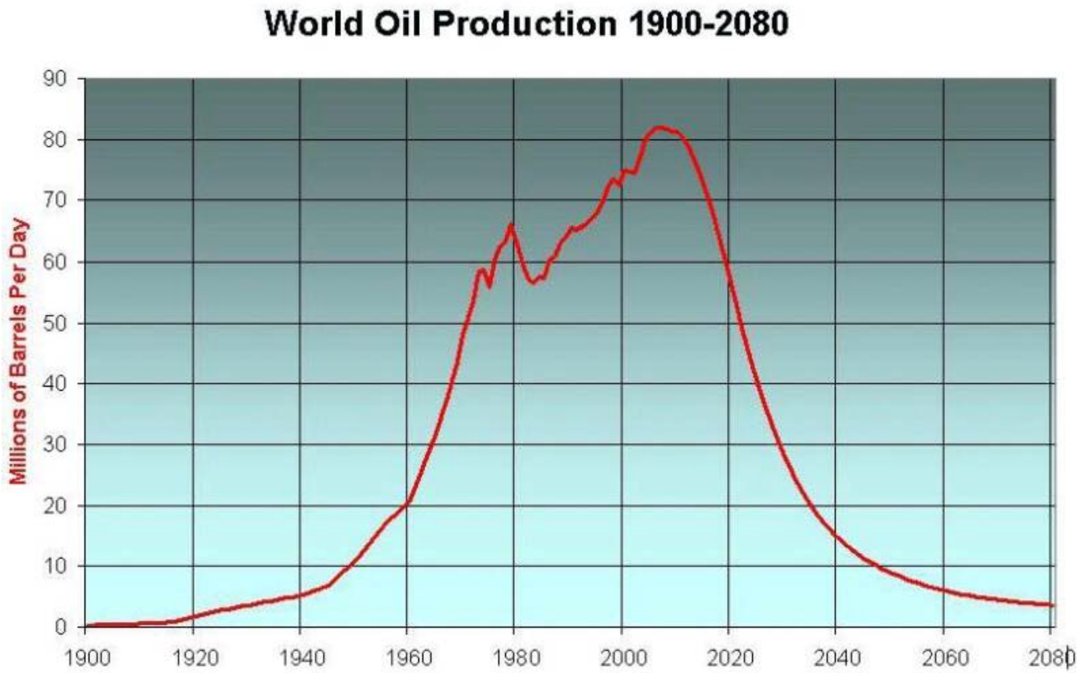
Present and Future Projects: DEMO



What if..?

- ITER does not work?
  - Magnetic fusion on the basis of TOKAMAKs is not an option for the future. The answer is clear.
- If cost go up, schedule slips, technical issues arise?
  - ITER Council: “manage the cost, minimize any delay but get us there as soon as possible”
- What if DEMO takes longer?
  - Still many energy resources exist. Mostly fossile. There will be enough for about another 100-150 years…. but

ITER – a Global Challenge



„The stakes are considerable, not to say vital for our planet."

Manuel Barroso, Former President of the European Commission

End

Flagship Tokamaks

- ITER: (International Thermonuclear Experimental Reactor)
- JET: (Joint European Torus)
- JT-60: (Japan Tokamak (?))
- TFTR: (Tokamak Fusion Test Reactor)
- TPX: (Tokamak Physics Experiment)

Medium to Large Tokamaks

- Alcator C-Mod:
- ASDEX-U: (Axially Symmetric Divertor EXperiment-Upgrade)
- DIII-D: (Doublet III, D-shape)
- FT: (Frascati Tokamak)
- NSTX: (National Spherical Tokamak eXperiment)
- PBX-M: (Princeton Beta Experiment-Modified)
- TCV: (Variable Configuration Tokamak - in French)
- TdeV: (Tokamak de Varenne)
- TEXTOR:
- Tore Supra:
- EAST
- KSTAR

Small Tokamaks

- CDX-U (Current Drive eXperiment-Upgrade)
- START: (Small, Tight-Aspect-Ratio Tokamak)
- TEXT-U: (Texas Experimental Tokamak-Upgrade?)

Stellarators

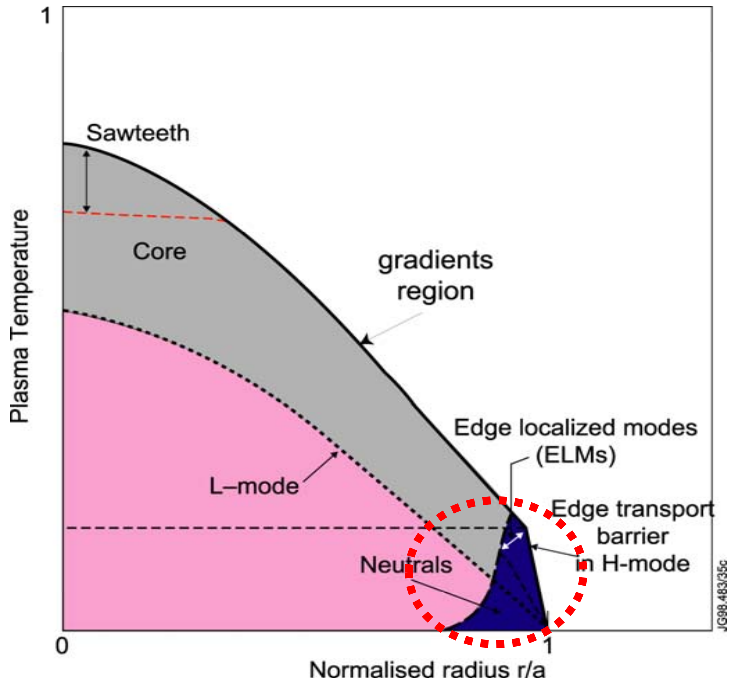
- ATF (Advanced Toroidal Facility)
- Wendelstein-7AS: (Advanced Stellarator)
- Wendelstein-7X
- LHD

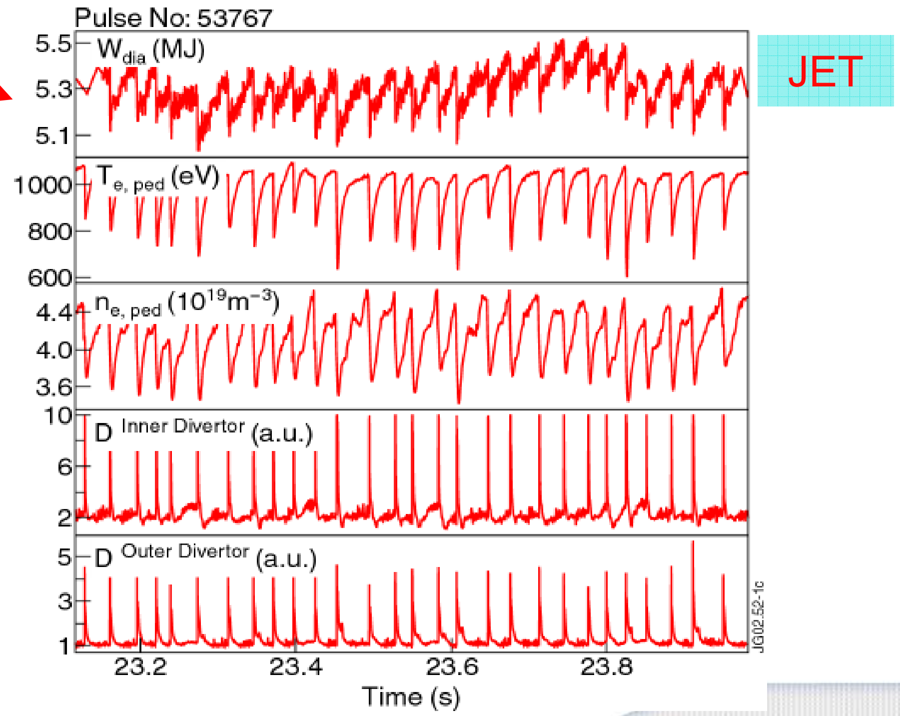
Inertial Confinement

- NIF: (National Ignition Facility)
- Nova:
- Omega:
- NIKE
- LMJ

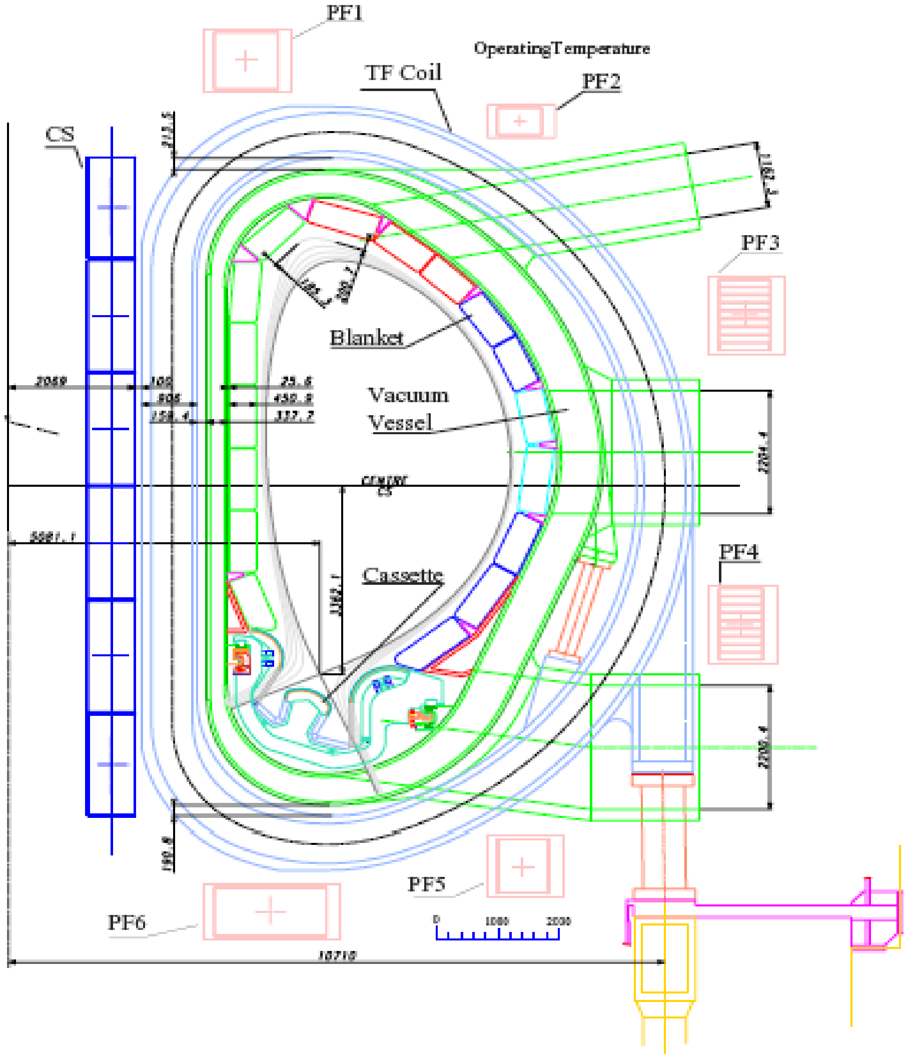
ITER Plasma Scenario - ELMy H-mode

- Conventionally, plasma confinement regimes denoted L-mode and H-mode
  - The difference between these modes is caused by the formation of an edge pedestal in which transport is significantly reduced - edge transport barrier
  - edge localized modes maintain plasma in quasi-stationary state





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	³ 10
Fusion power	~400 MW
Plasma burn duration	~400 s

A detailed engineering design for ITER was delivered in July 2001