
Overview and challenges of the ITER Project

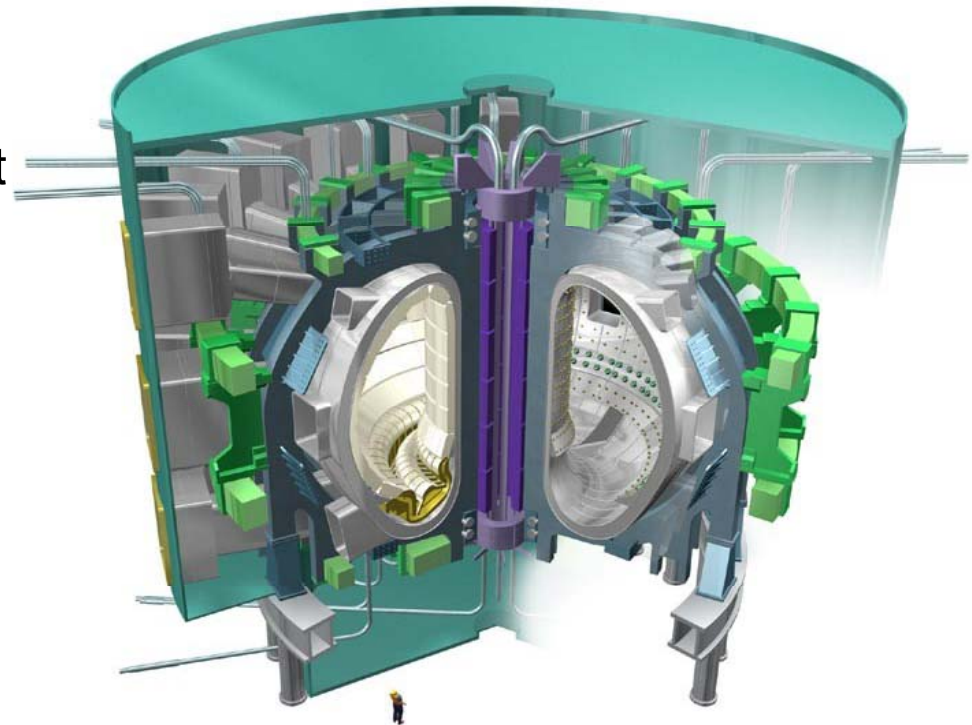
**Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, Aosta Valley, Italy**

5 March 2009

Norbert Holtkamp
Principal Deputy Director General of the ITER Organization

ITER – The way to fusion power

- ITER (“the way” in Latin) is the essential next step in the development of fusion.
- Its objective: to demonstrate the scientific and technological feasibility of fusion power.
- The world’s biggest fusion energy research project, and one of the most challenging and innovative scientific projects in the world today.



ITER – Key Facts

Mega-Science Project among 7
Members:

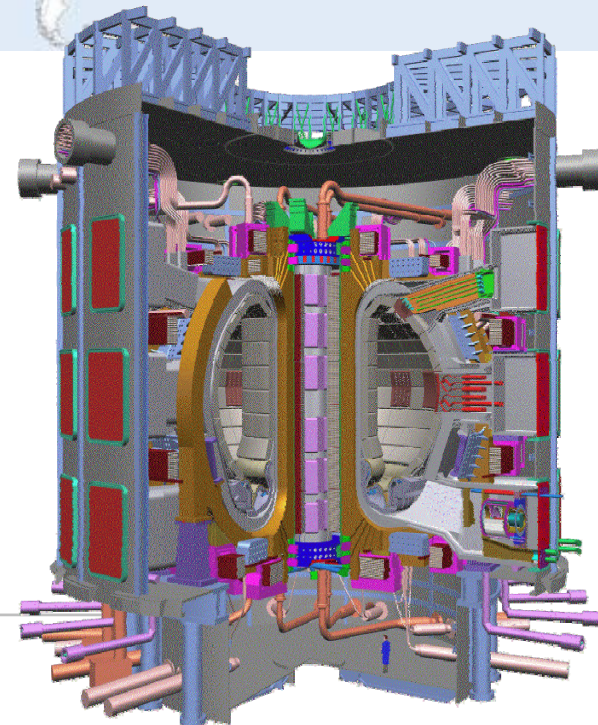
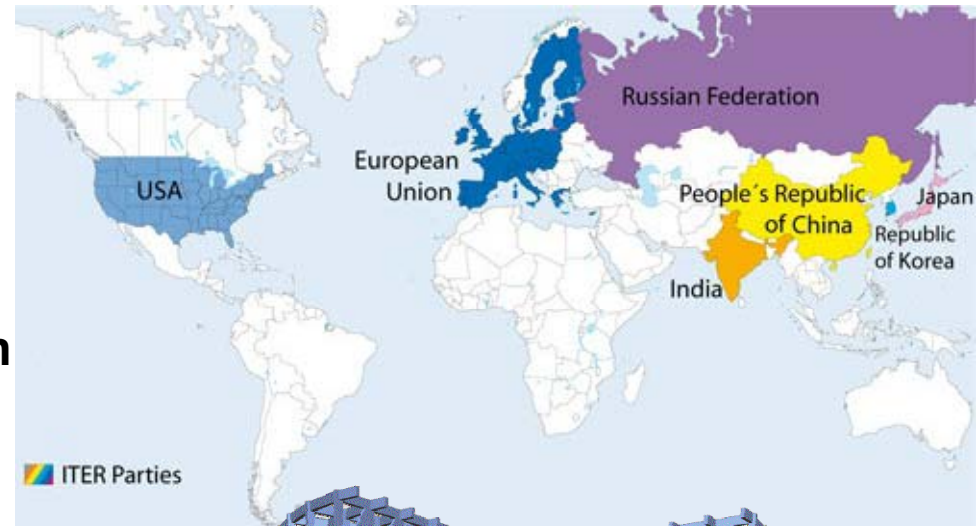
**China, EU, India, Japan, Korea,
Russia & US**

Designed to produce 500 MW of fusion
power for an extended period of time

Will bring together most key
technologies needed for future fusion
power plants

10 years construction, 20 years
operation

Cost (official): **~5.5 billion Euros for
construction**, and ~5.5 billion for
operation and decommissioning



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 24: ratification of the Joint ITER Agreement (apart from US)

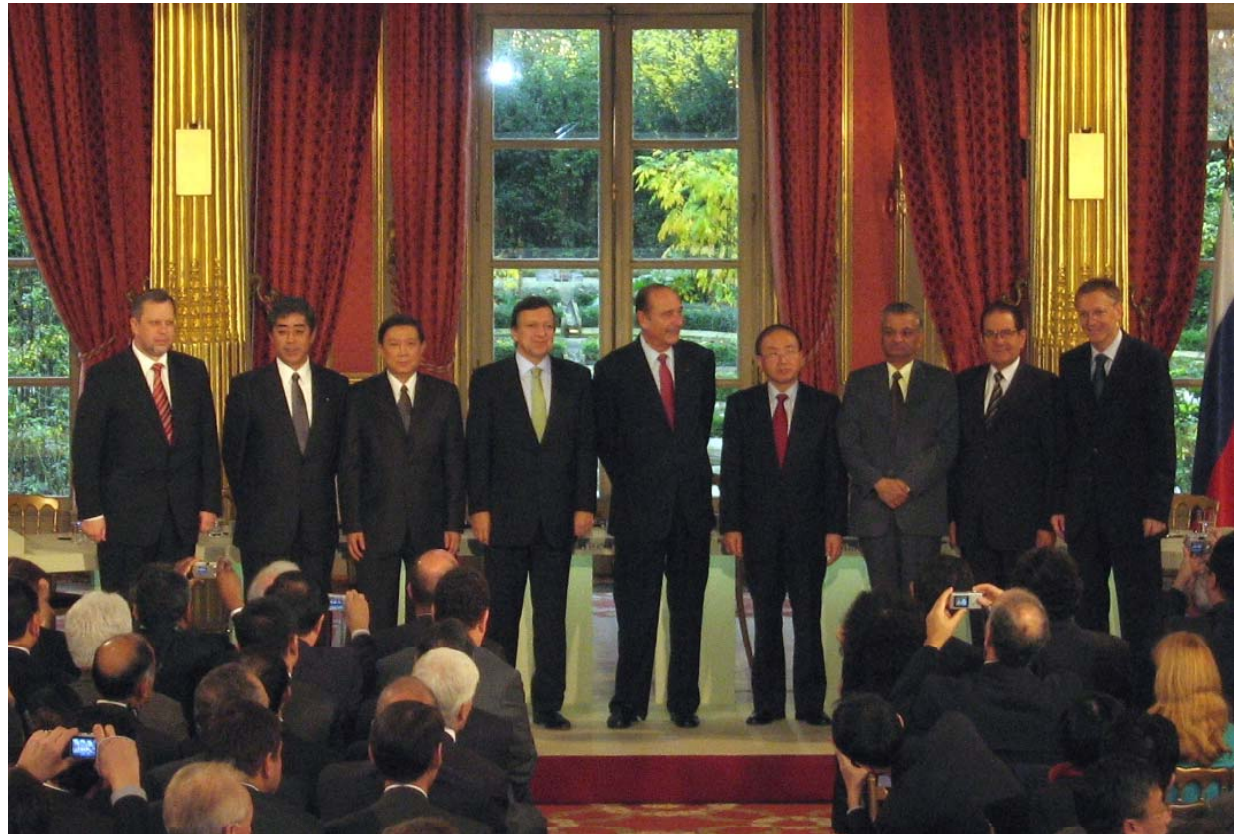
2008

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



The ITER Agreement

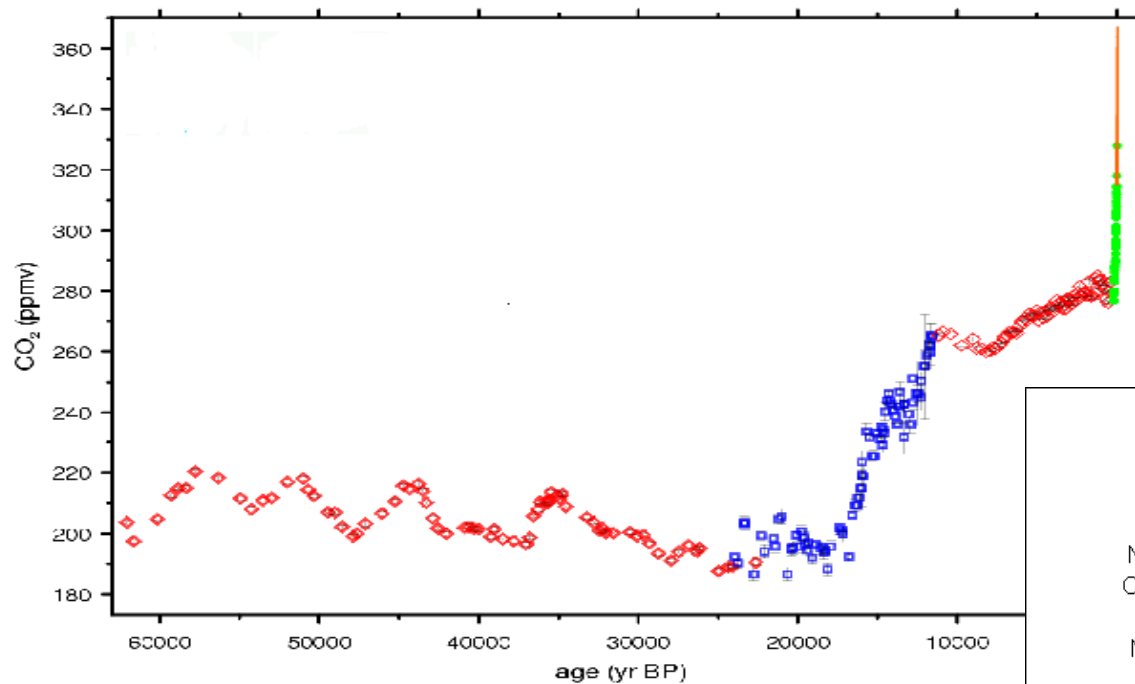
On November 21, 2006, the ITER Agreement was signed at the Elysee Palace in Paris by the seven parties China, Europe, India, Japan, Korea, Russian Federation and the United States of America.



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

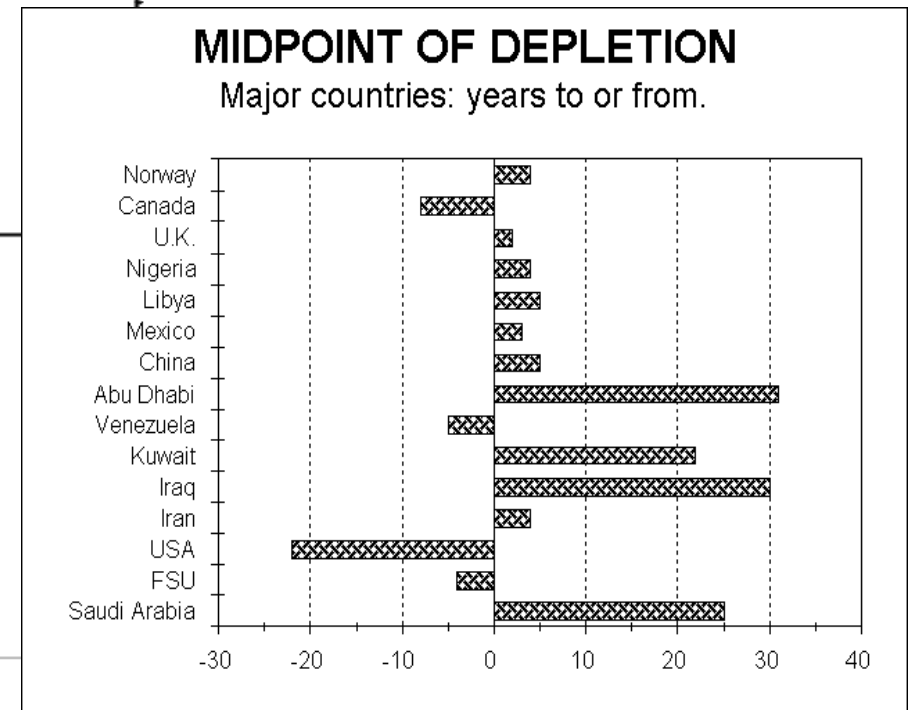


Global Warming and How much is left?

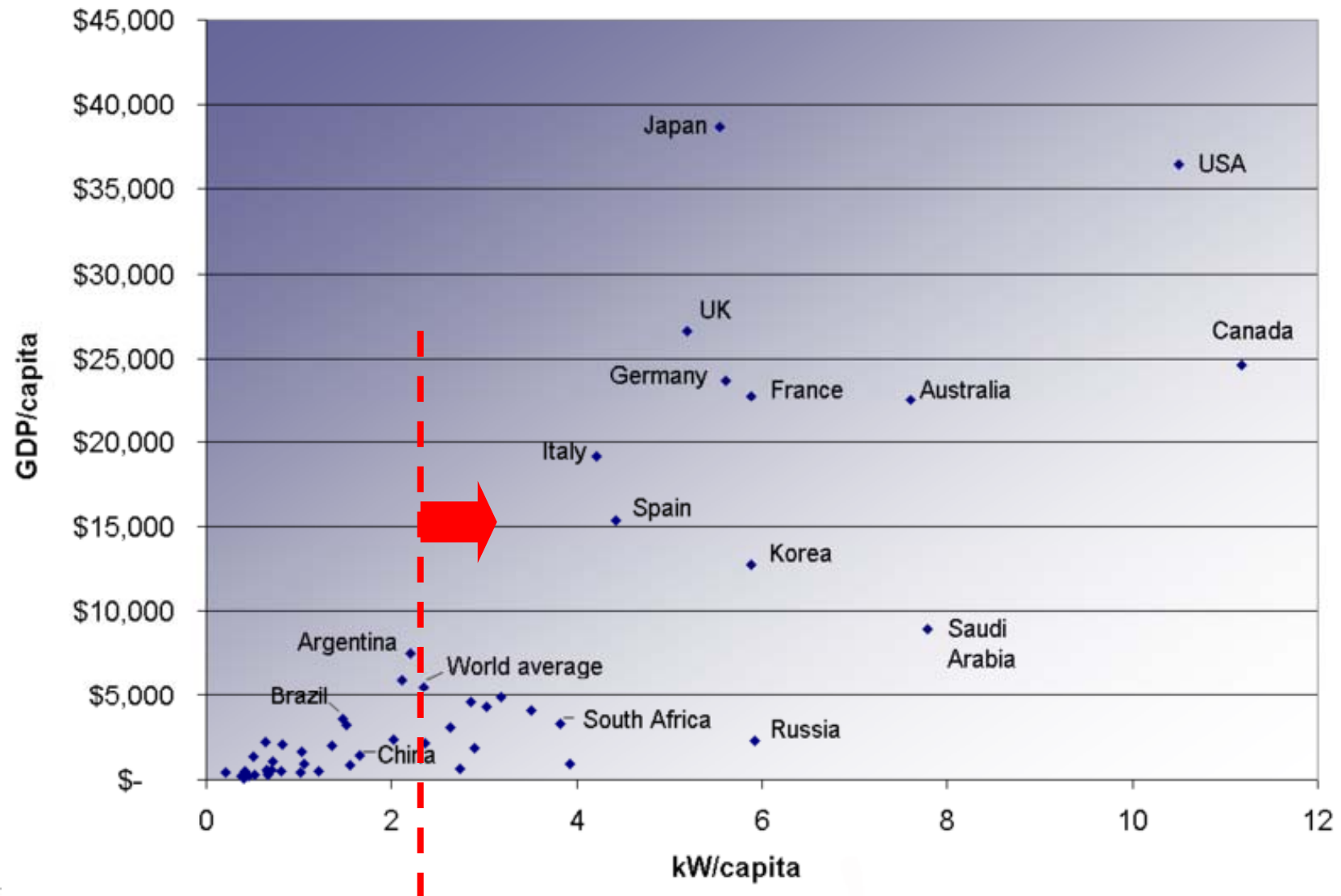


60 000 year CO₂ level

Oil reserves

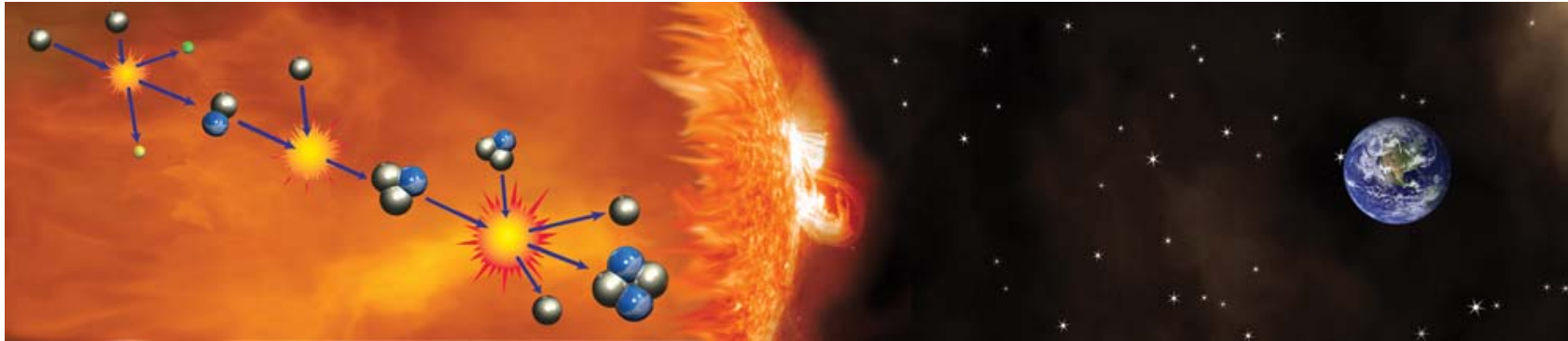


The Energy Dilemma



Fusion powers the sun and the stars

“...Prometheus steals fire from the heaven”



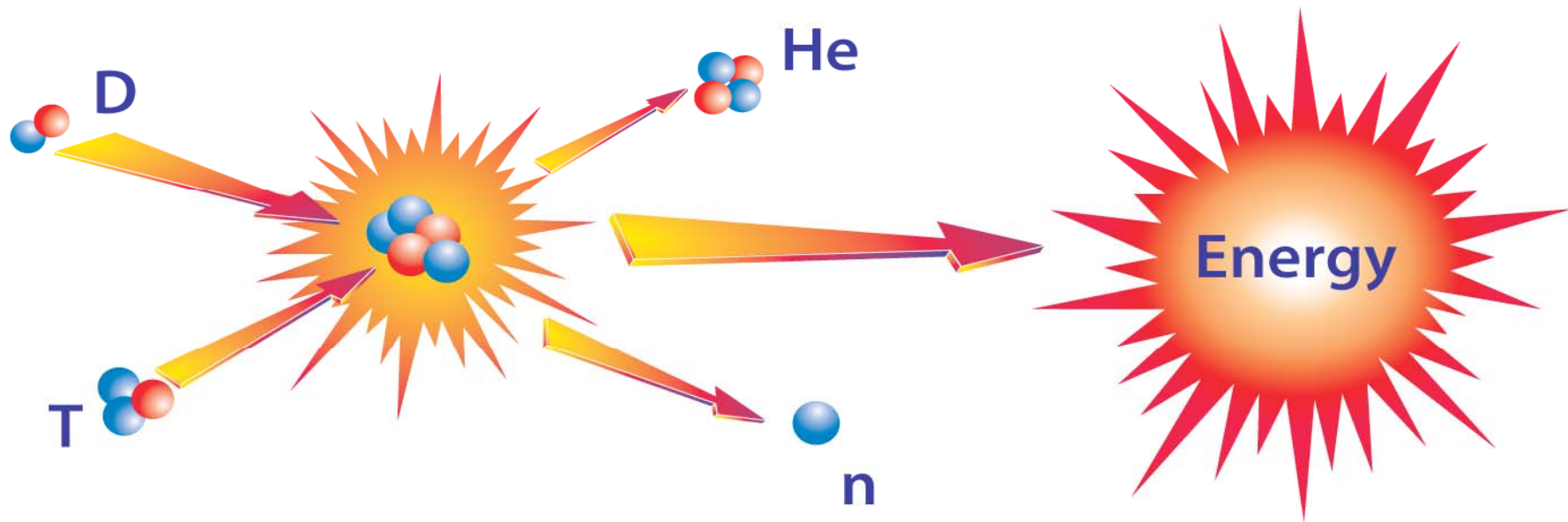
**On Earth,
fusion could provide:**

- Essentially limitless fuel, available all over the world
- No greenhouse gases
- Intrinsic safety
- No long-lived radioactive waste
- Large-scale energy production

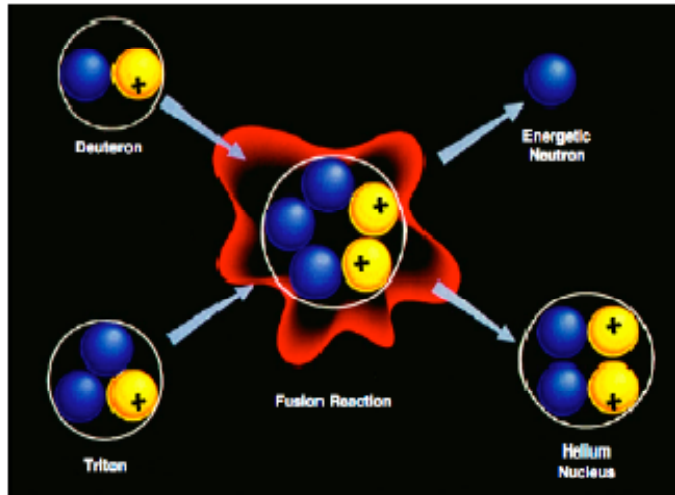
The Fusion Reaction on Earth

“... is not the same as in the Sun”

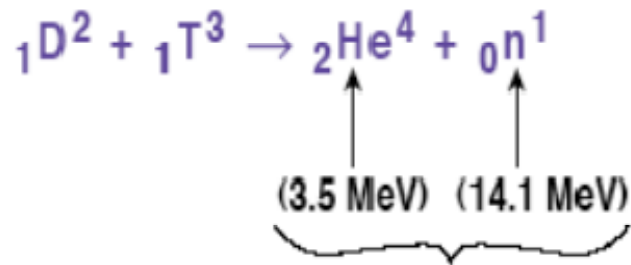
- $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 5.5 \text{ eV}$ (chemical)
- $4^1\text{H} + 2\text{e}^- \rightarrow 4^4\text{He} + 2\nu + 6\gamma + 26.7 \text{ MeV}$ (solar process)



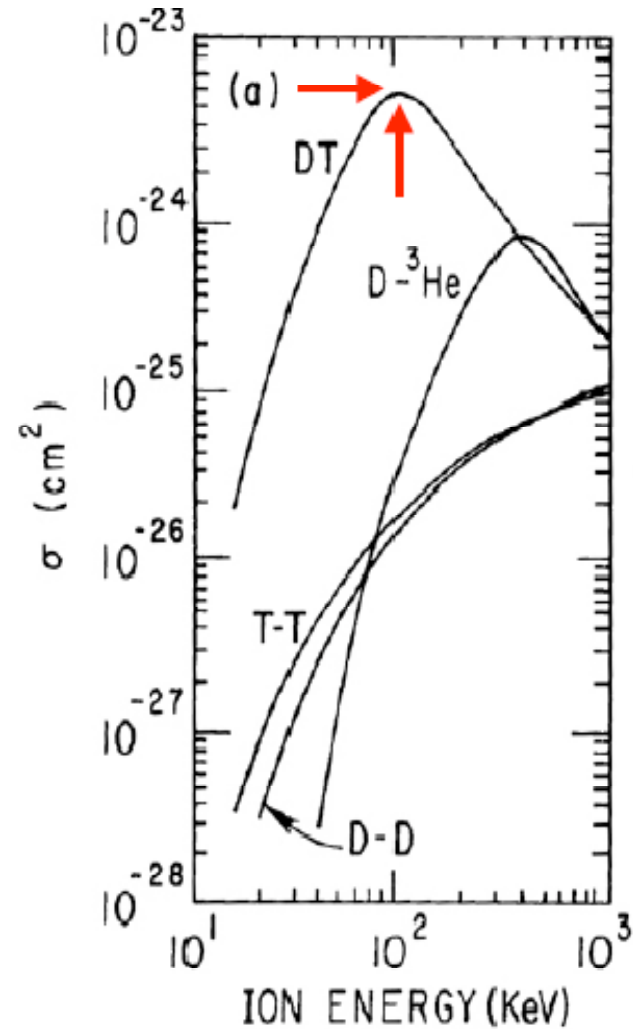
Why D-T: Cross section



The “easiest” fusion reaction uses hydrogen isotopes: deuterium (D) & tritium (T)



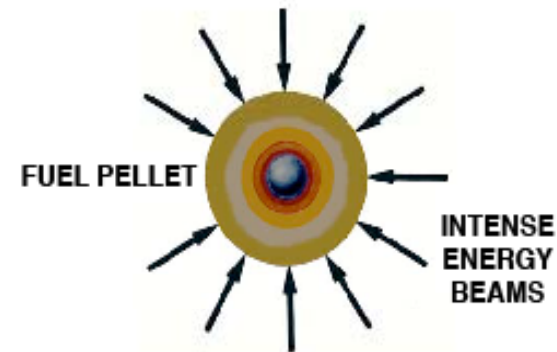
Energy/Fusion: $\epsilon_f = 17.6 \text{ MeV}$



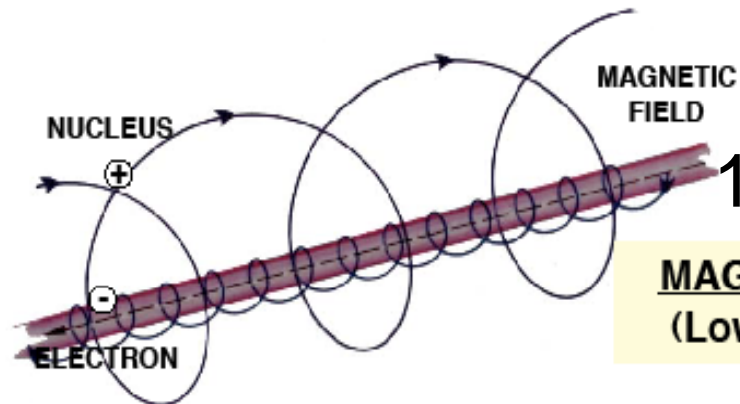
Nuclear cross sections

Three Ways to Fusion in the Universe

**GRAVITATIONAL
CONFINEMENT**
(High density for
billions of years)



INERTIAL CONFINEMENT
(High density for less than a
billionth of a second)

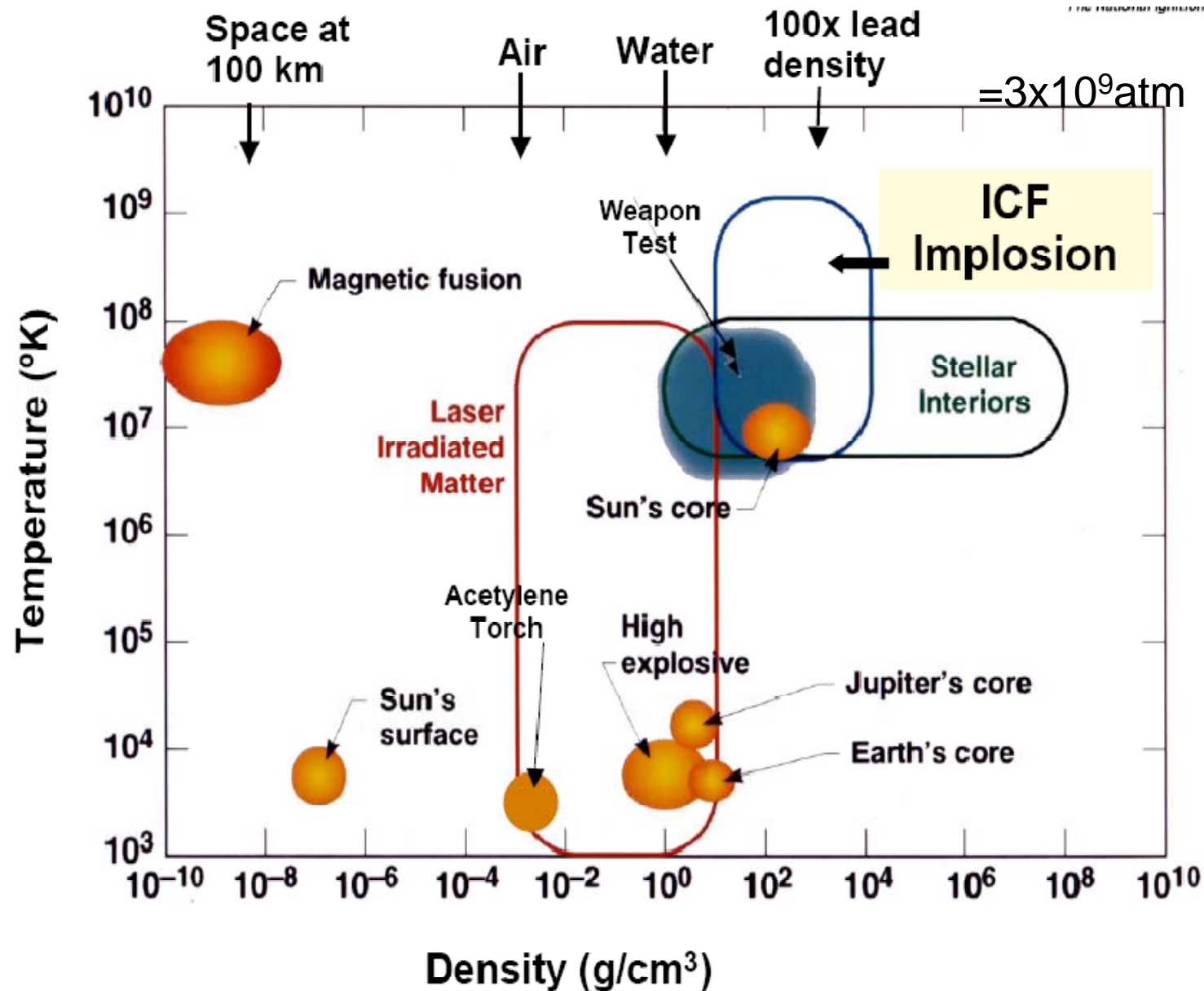


100-200 Million degree

MAGNETIC CONFINEMENT
(Low density for seconds)

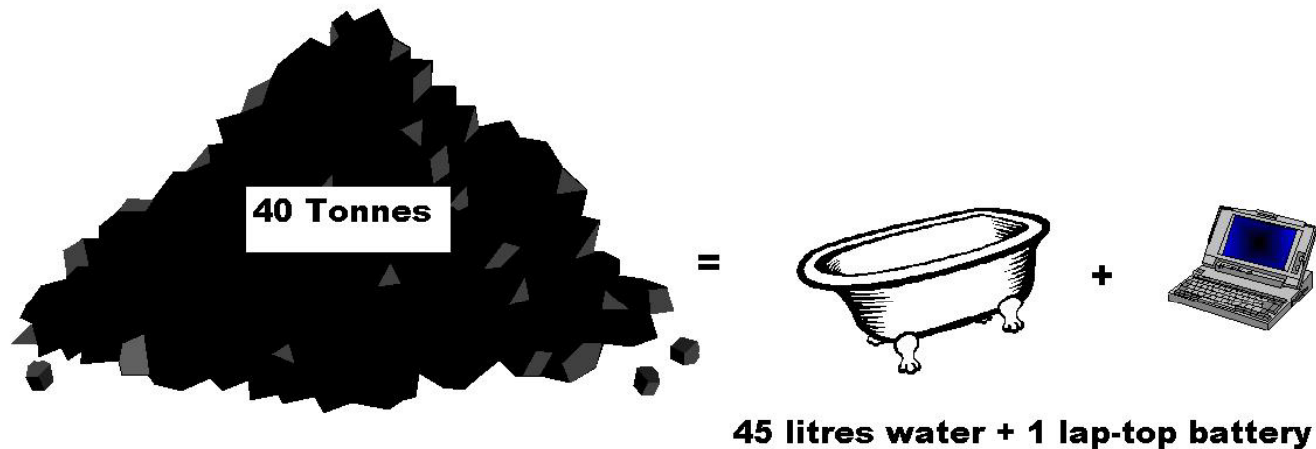
Will not talk about cold fusion !

Fusion in the Universe



Limitless Fusion Fuel

Raw fuel of a fusion reactor is water and lithium*

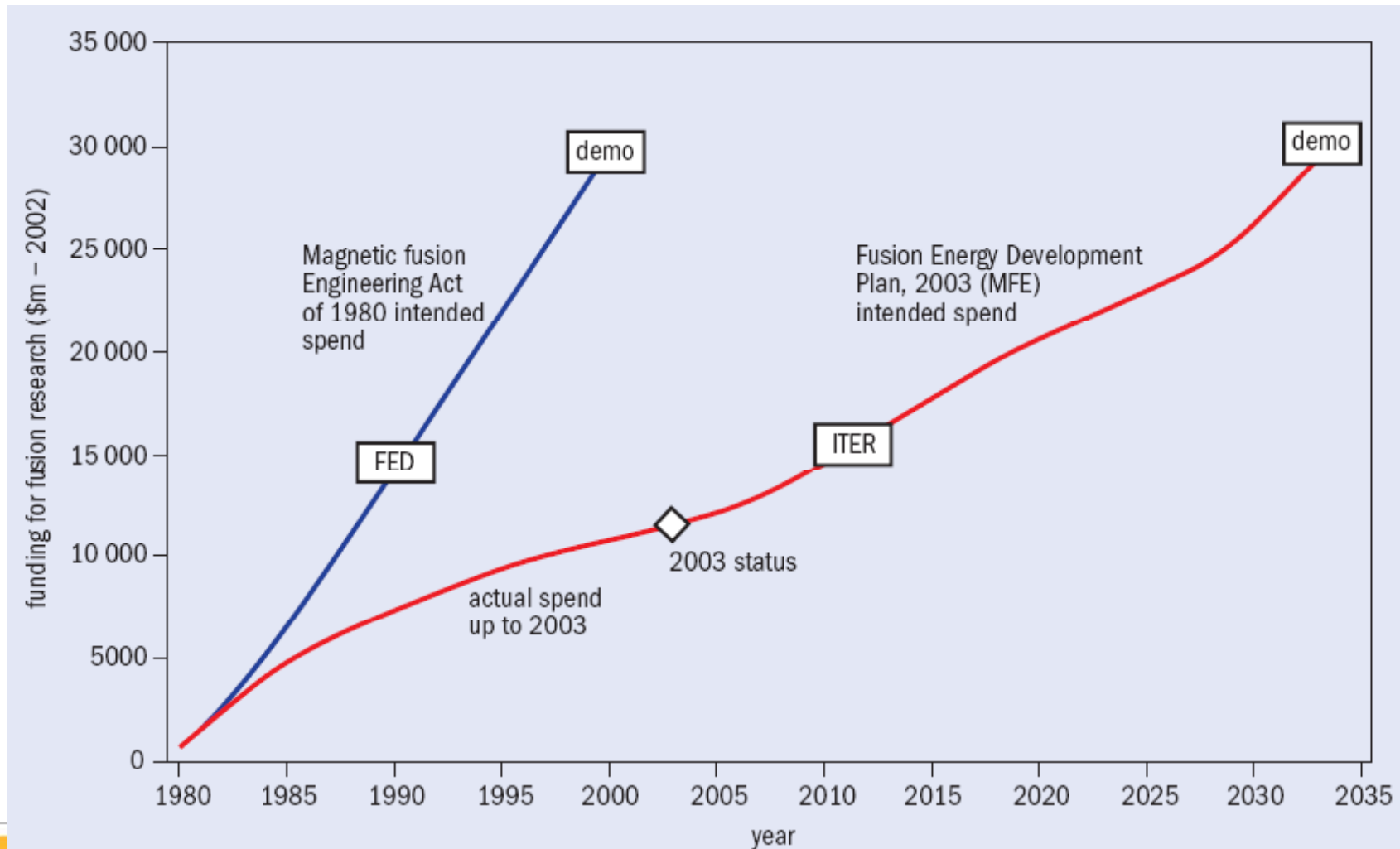


Lithium in one laptop battery + half a bath-full of ordinary water (-> **one egg cup full of heavy water**) 200,000 kW-hours
= (current UK electricity production)/(population of the UK) for 30 years

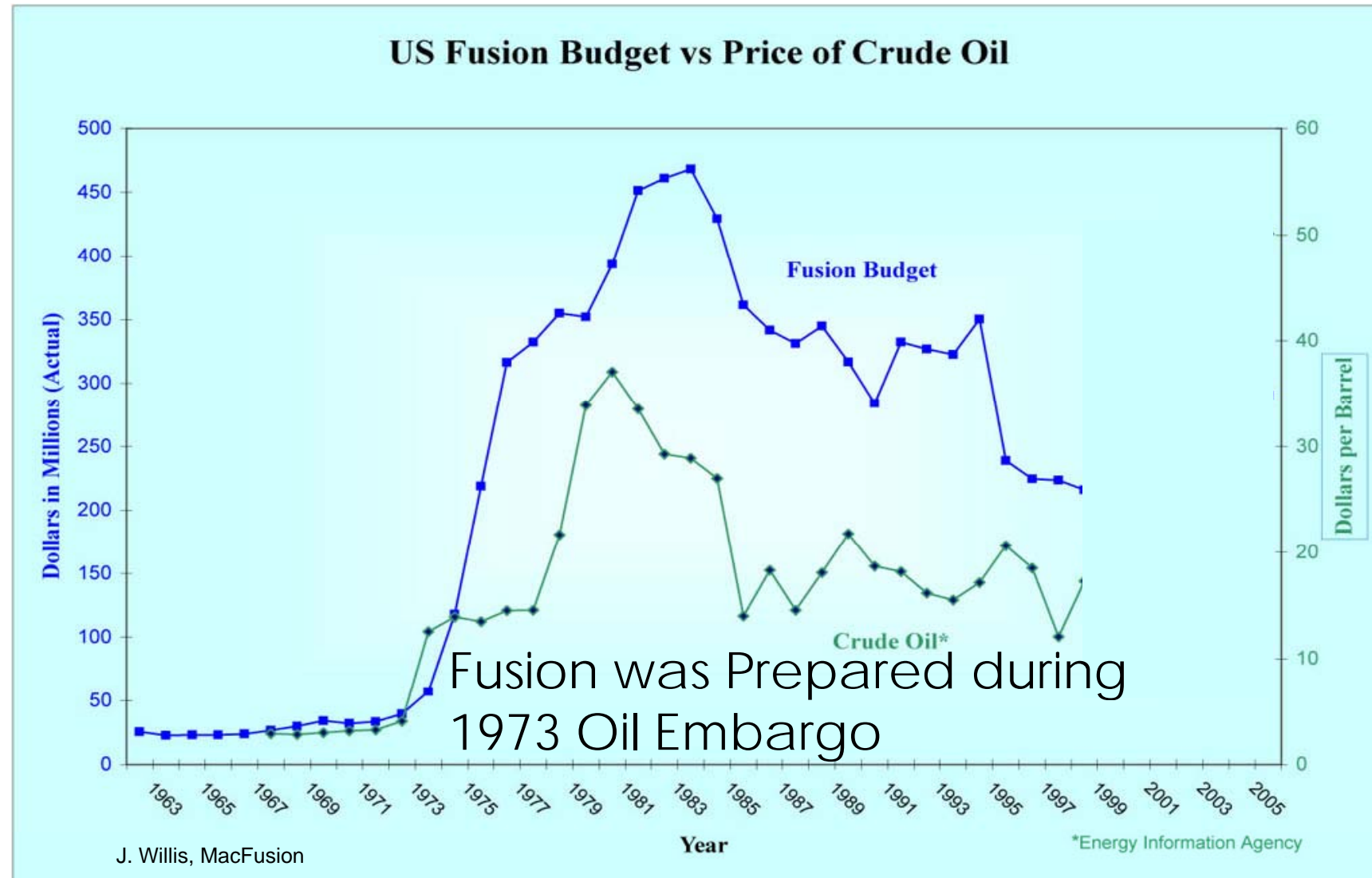
* **Deuterium/hydrogen** = 1/6700
+ **tritium from: neutron (from fusion) + lithium** → **tritium + helium**

Fusion is always 50 years away ?

One reason certainly: the funding to follow up on the plan was never made available



Fusion was Prepared during 1973 Oil Embargo but afterwards



Fusion History: The Russian Point of View...

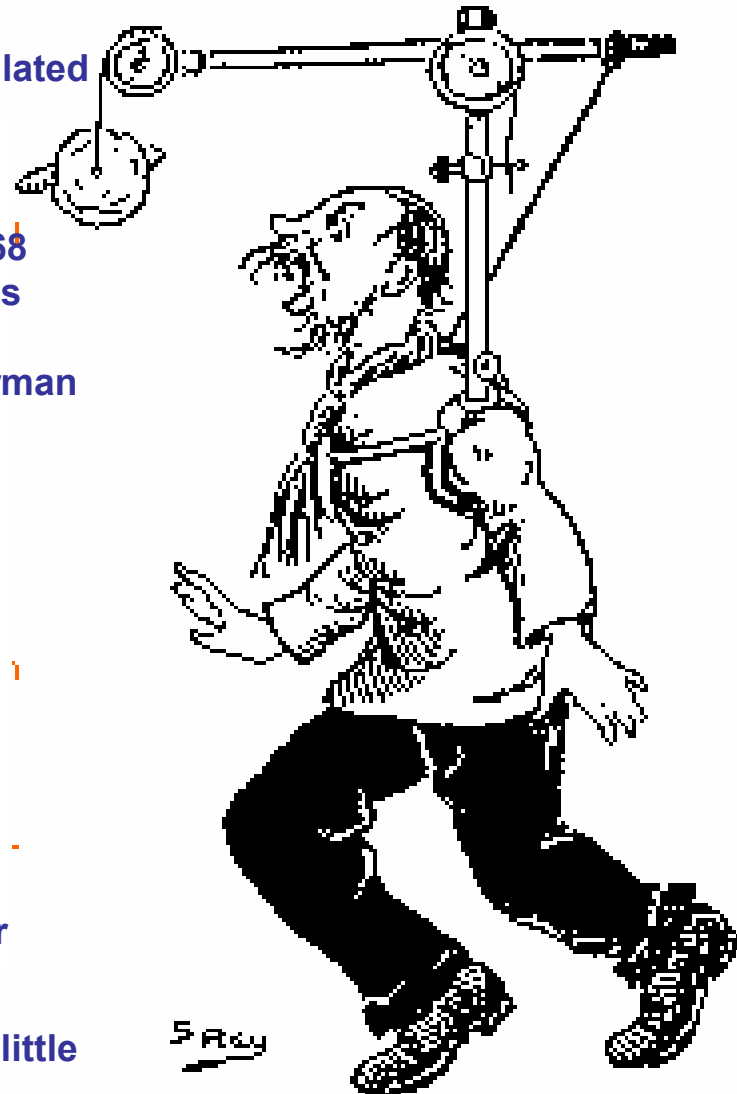
- 1928.G.Gamov -the theory
- 1930.Olifant,Kurchatov,Sinelnikov, exp.- proton beam, Li target
- 1932.Bucharin proposals to Gamov: Moscows electricity every night!
- Gamov left USSR
- 20 years pausa
-*not quite correct!!!*

E. Velikhov; AAAS 2008 Annual Meeting

What did the Fusion Community Promise?

A short history of Fusion

- $E = M * C^2$
- 1900: “the Mass deficit” on the sun
- 1920: Hydrogen to Helium “burning” process was speculated
- 1928: Gamow uses “tunnel effect” to explain fusion
- 1934: Rutherford $D+T \Rightarrow He$
- C.F. Weizsäcker/H.Bethe: Proton-Proton chain
- 1939: H. Bethe, ‘Energy Production in Stars’; Nobel P 1968
- 1945: Fermi+Teller: Magnetic confinement of hot plasmas
- 1946: first patent in Britain
- 1951: Péron and the Stellarator; R. Richter: Austrian/German
- 1951: L. Spitzer: Stellarator experiment in Princeton. –
- 1950: Sacharow+Tamm first linear device:
 - 1955: first TokamakTMP
- 1955: J.D. Lawson: “Lawson Criterion”
- 1957: ZETA
- 1958: Kurchatov announced effort of Nuclear Fusion
- 1968: L.Artsimowitsch: “Confinement” and the way to “break” even.
- Europe: 1958 foundation of Euratom and the way to JET which was planned in England, thought to be build in Garching and finally began operation in 1983 in Culham.
- Chernobyl disaster led to a decreased interest in nuclear energy...(56 direct death, 47 emergency workers, ~6000 cancer cases)
- In the middle of the '90s: price per barrel ~20\$, and very little investment was done in alternative energies...



The dangling “Carrot”

Lawson: The Fusion Lingo

- Confinement Time

$$\tau = \frac{\text{Energy in the Plasma}}{\text{Energy lost per sec}}$$

- Density

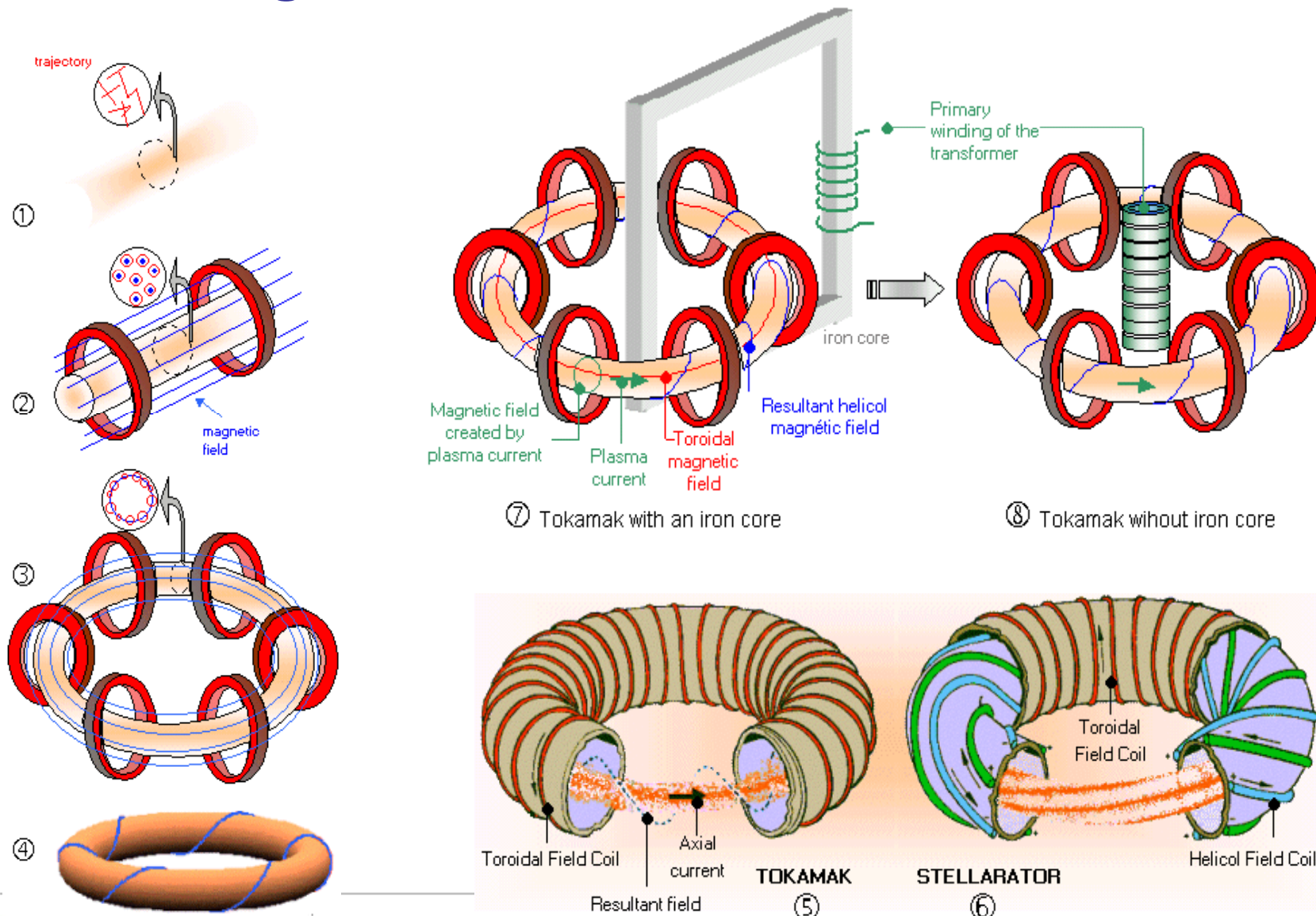
$$n = 1 - 2 \times 10^{20} \text{ particles} \cdot \text{m}^{-3}$$

- Temperature

$$100 - 200 \times 10^6 \text{ Kelvin}$$

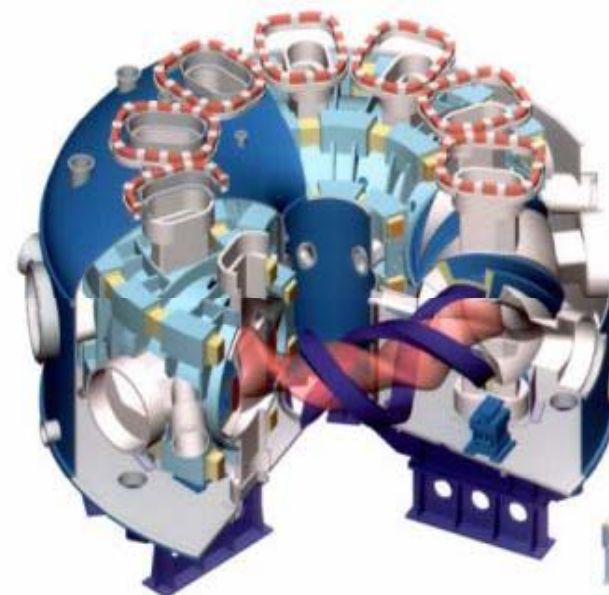
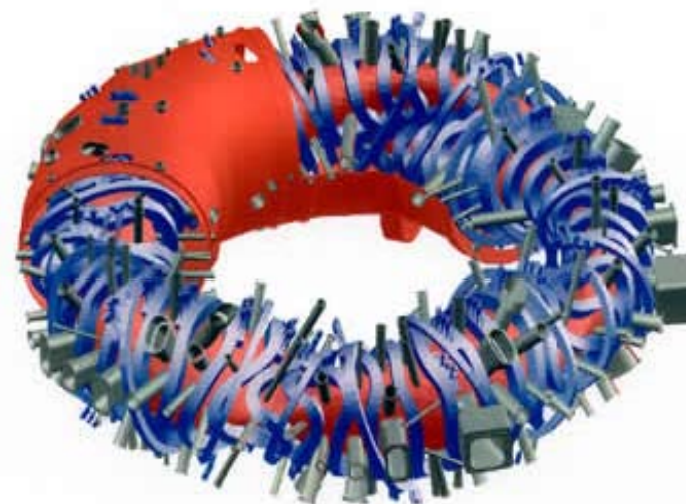
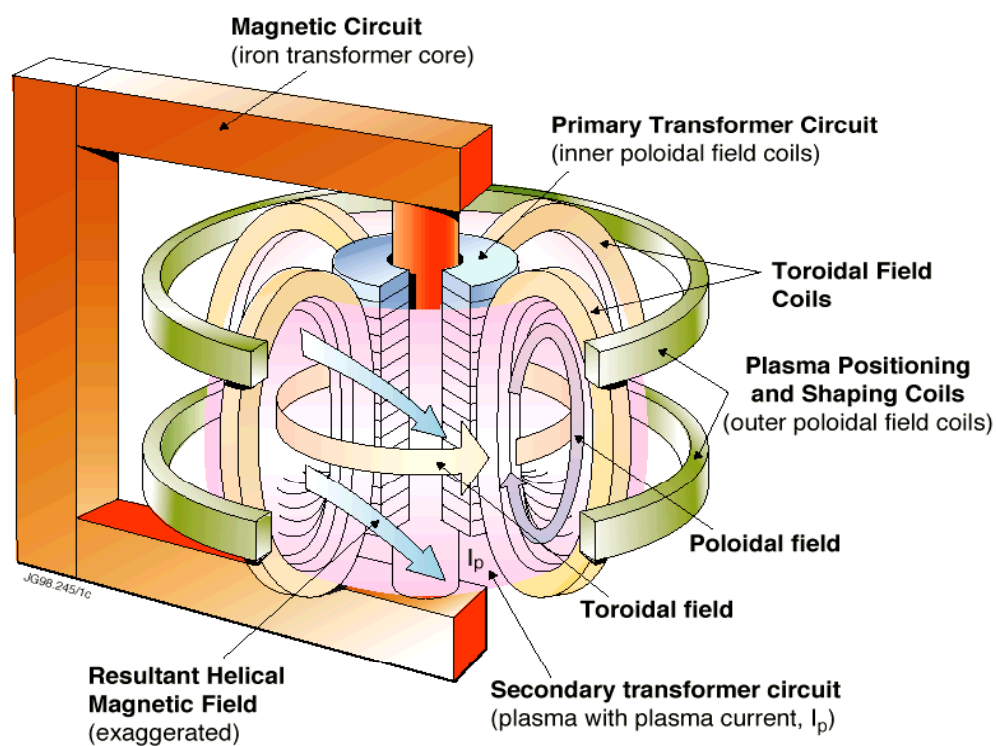
$$\tau \cdot n \cdot T \geq 3 \cdot 10^{28} \frac{\text{Kelvin}}{\text{m}^3 \cdot \text{sec}}$$

Basic Principle of Stable Motion of Ions in Magnetically confined Plasma



Tokamak and Stellarator

"тороидальная камера в магнитных катушках"
(*toroidal'naya kamera v magnitnykh katushkakh*) —
toroidal chamber in magnetic coils (Tochamac)).



The First Devices



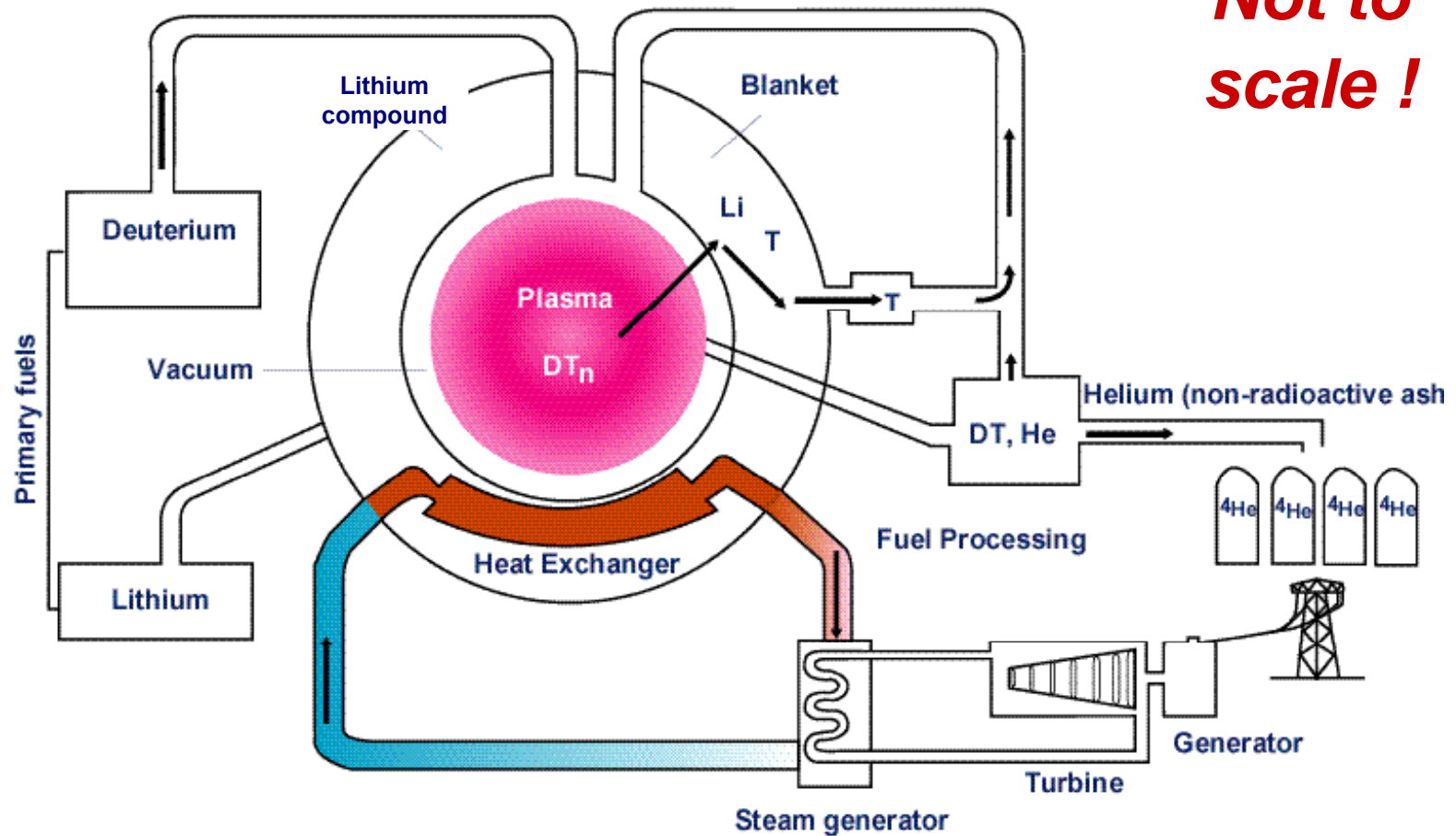
IAEA: 1958 First Geneva Conference

The 40's-50's: ZETA



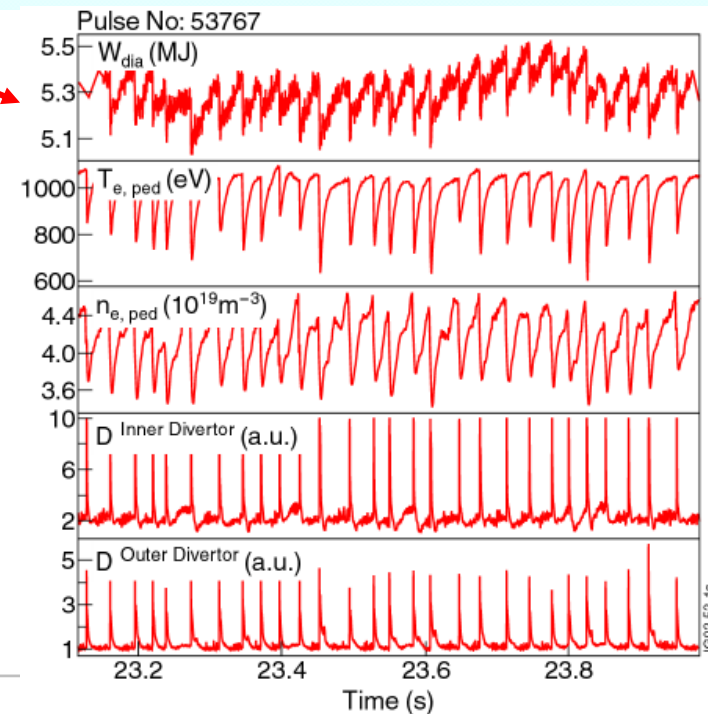
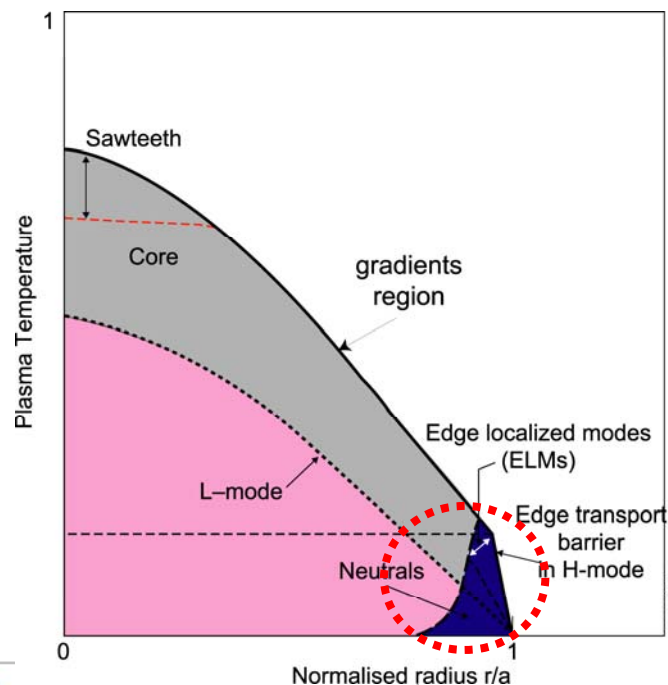
A Fusion power plant would be like...

Not to scale !



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



JET

JET: The Key Facility

- JET: 16 MW of fusion power ~ equal to heating power.
- Ready to build a Giga Watt-scale tokamak: ITER



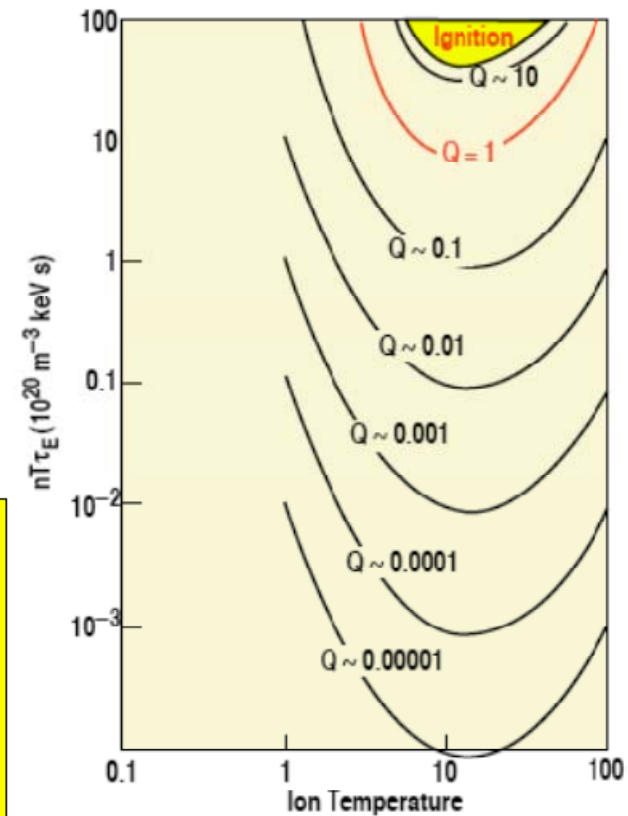
Definition of Burning Plasma

$$\frac{dW}{dt} \rightarrow 0 \Rightarrow P_{\alpha} + P_{\text{heat}} = \frac{W}{\tau_E}$$

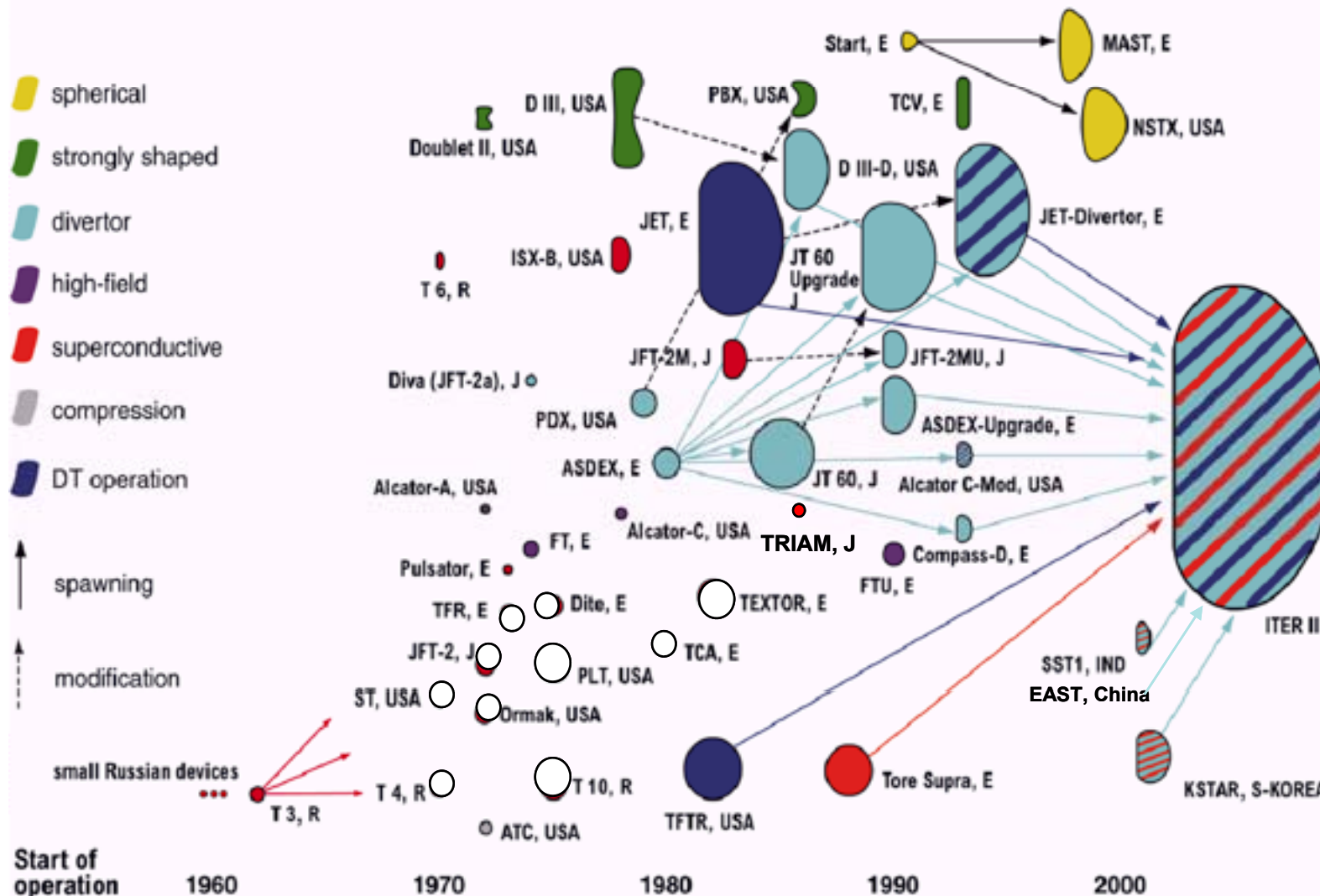
Define fusion energy gain, $Q \equiv \frac{P_{\text{fusion}}}{P_{\text{heat}}} = \frac{5 P_{\alpha}}{P_{\text{heat}}}$

Define α -heating fraction, $f_{\alpha} \equiv \frac{P_{\alpha}}{P_{\alpha} + P_{\text{heat}}} = \frac{Q}{Q+5}$

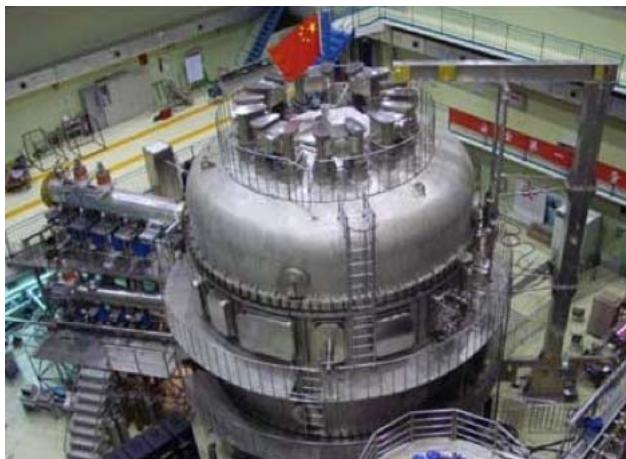
Breakeven	$Q = 1$	$f_{\alpha} = 17\%$
<hr/>		
Burning plasma regime	$Q = 5$	$f_{\alpha} = 50\%$
	$Q = 10$ (ITER)	$f_{\alpha} = 60\%$
	$Q = 20$	$f_{\alpha} = 80\%$
	$Q = \infty$ (ignition)	$f_{\alpha} = 100\%$



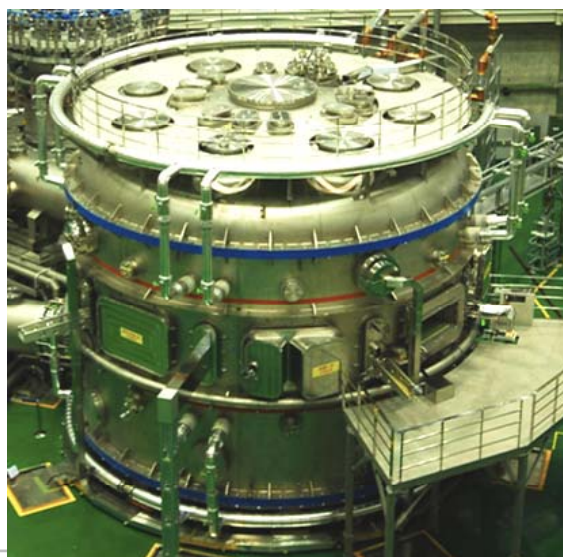
History of Tokamak's



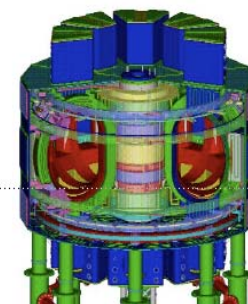
Four New Superconducting Tokamaks will Address Steady-State Advanced Tokamak Issues in Non-Burning Plasmas



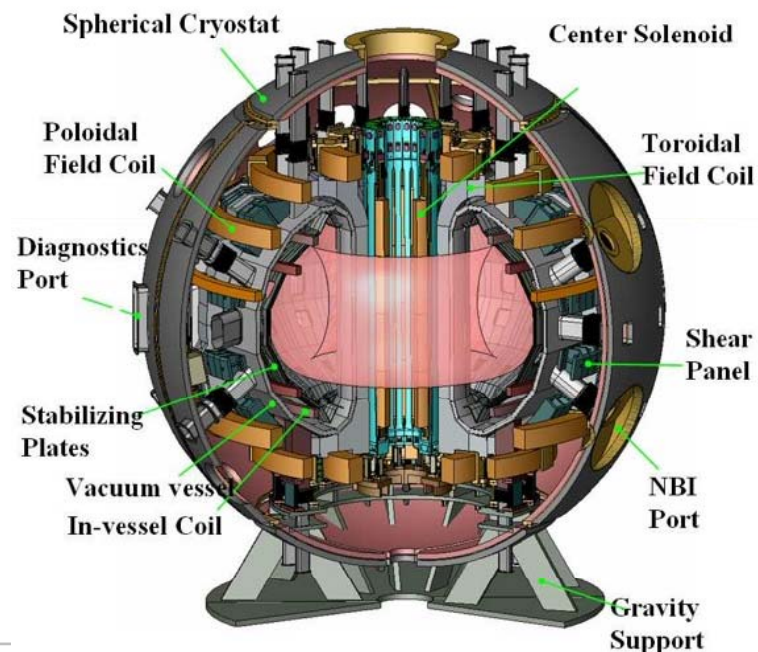
EAST: $R = 1.7\text{m}$, 2MA, 2006



KSTAR: $R = 1.8\text{m}$, 2MA, 2008

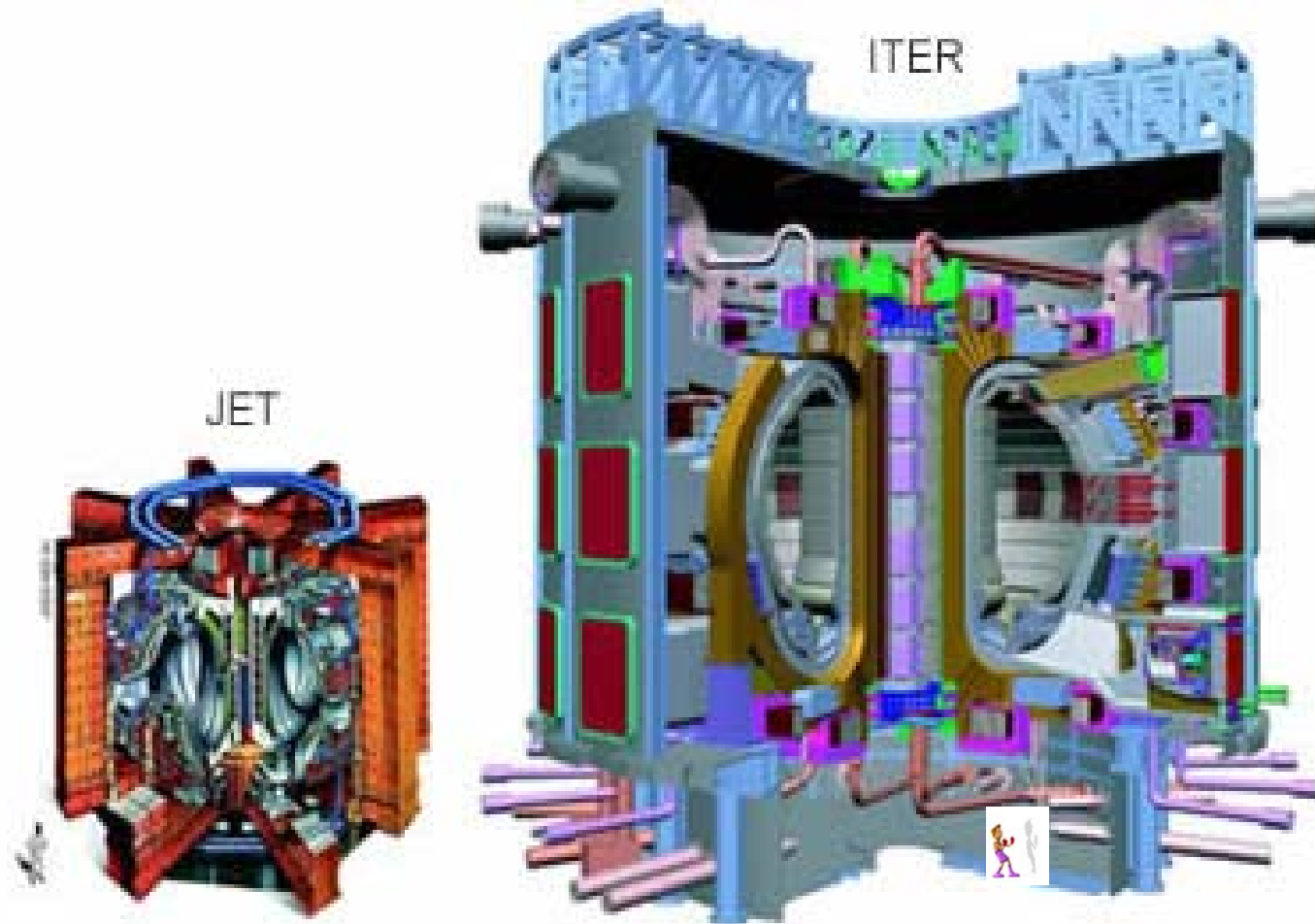


SST-1: $R = 1.1\text{m}$, 0.22MA, 2008

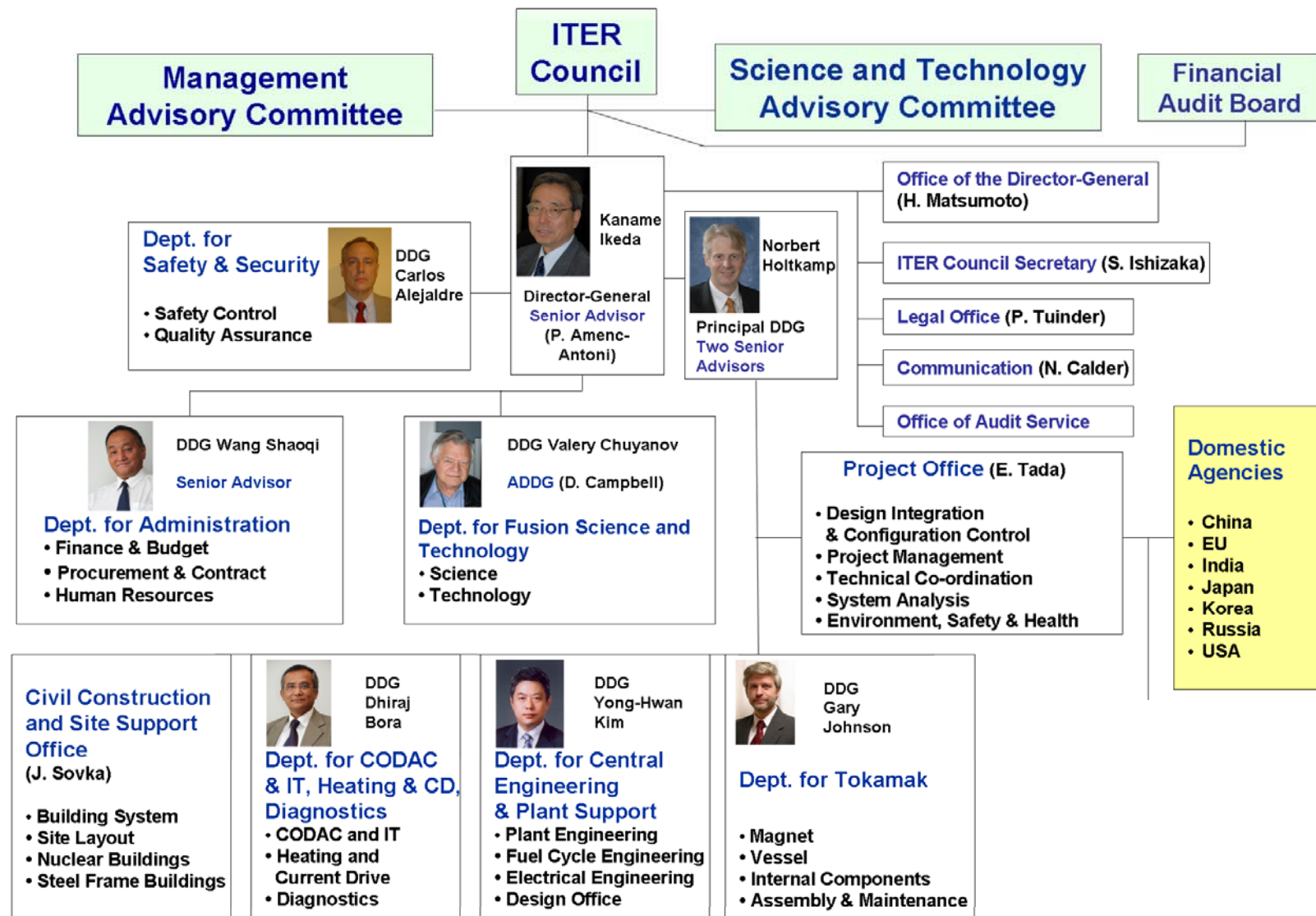


JT-60SA: $R = 3\text{m}$, 5.5 MA, 2014

JET/JT-60/TFTR → ITER



ITER Organization



The Personnel Working at the ITER Organization

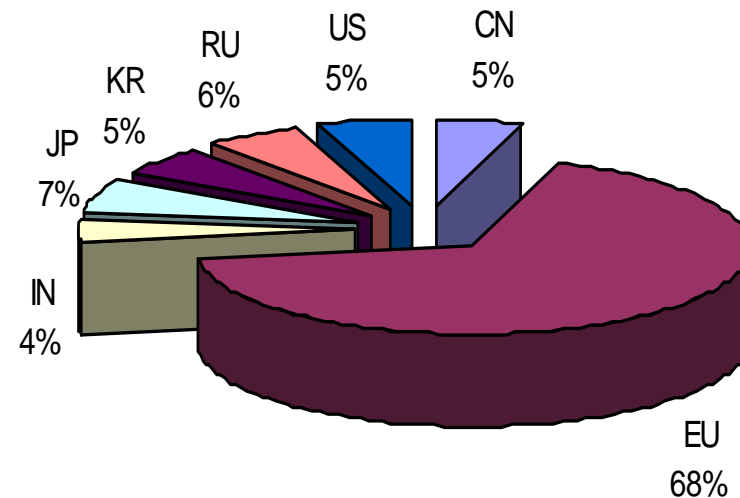
- Employees of the ITER Organization
(end January)

- 313 employees (67% from EU) : 231 professionals and 82 support staff
- 24 nationalities
- 129 recruitments ongoing
- plus: 5 «Visiting Researchers » for 2 to 3 years and personnel from the Domestic Agencies here for a couple of months

+ 32 interim work force

- >350 total staff in early 2009
- Construction peak >900
- World wide 3000-4000 people at peak

Total of 24 nationalities



Percentage of IO employees by
ITER Members

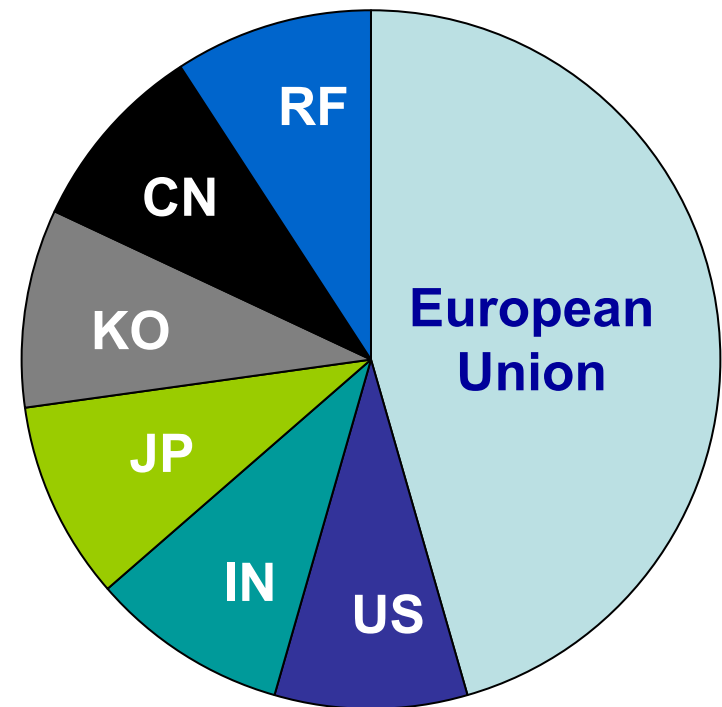
Construction Sharing

Overall sharing:

EU 5/11, other six parties 1/11 each. Overall contingency of 10% of total. Total amount: 3577 kIUA (5365 M€)

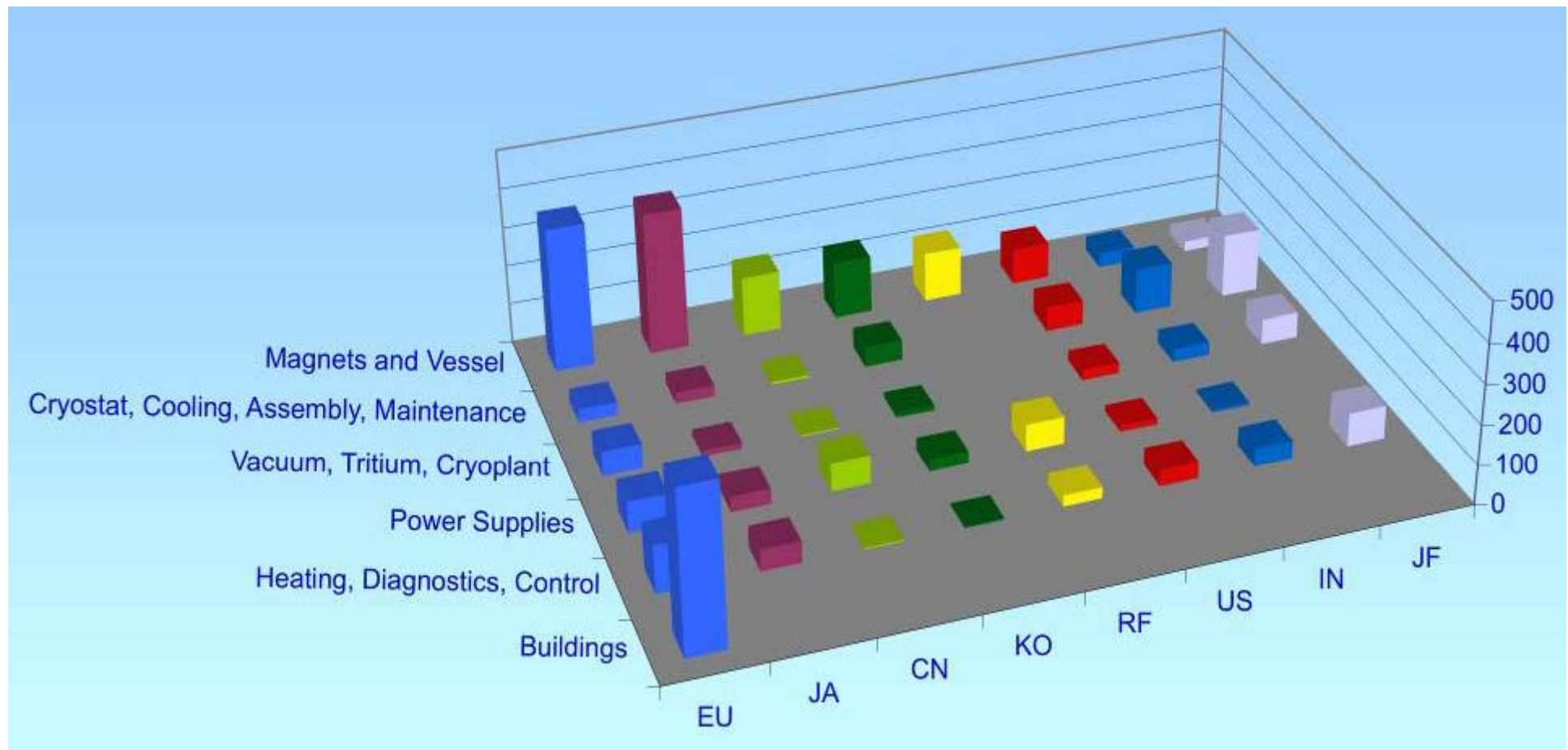


Divertor cassette during R&D phase

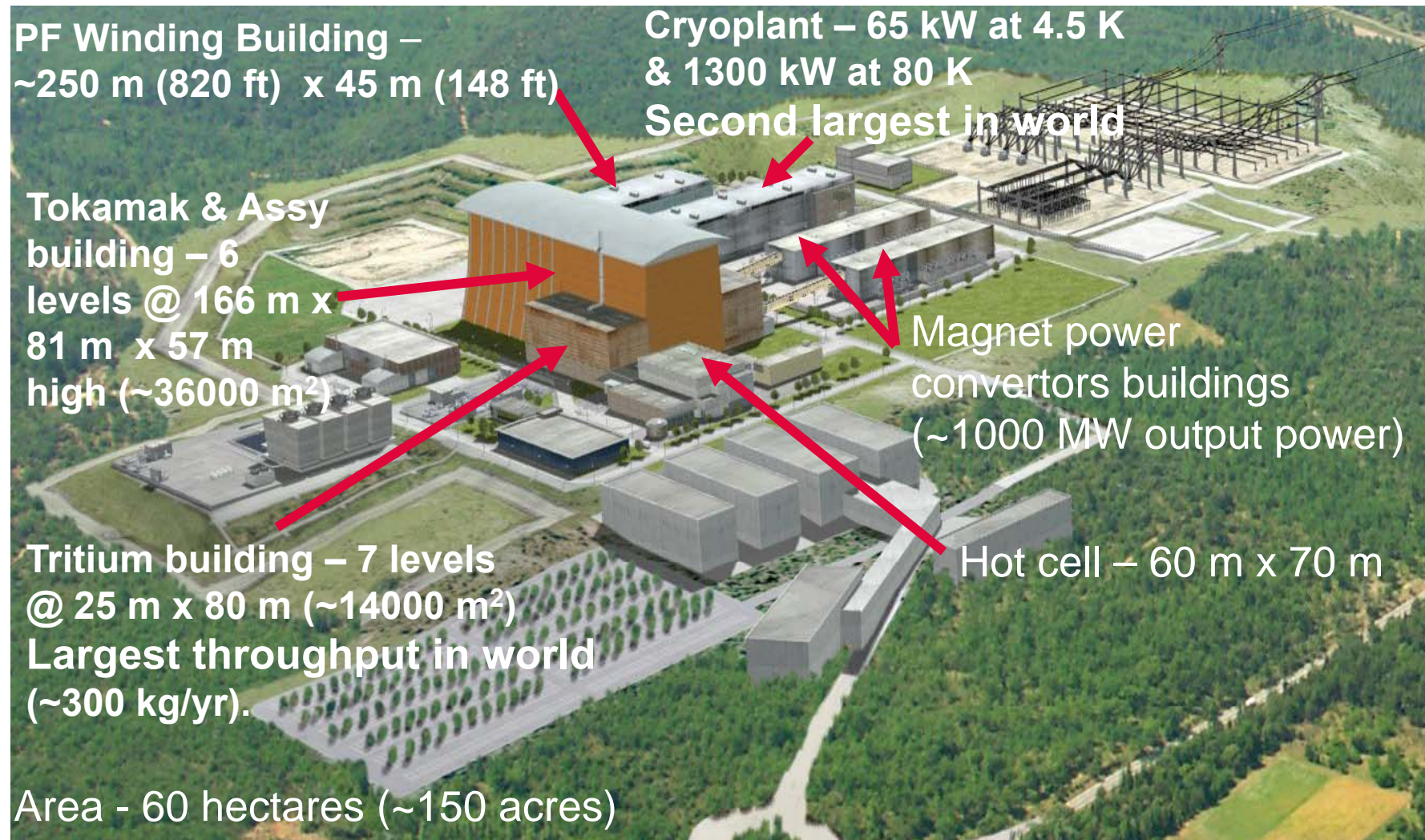


Procurement Sharing

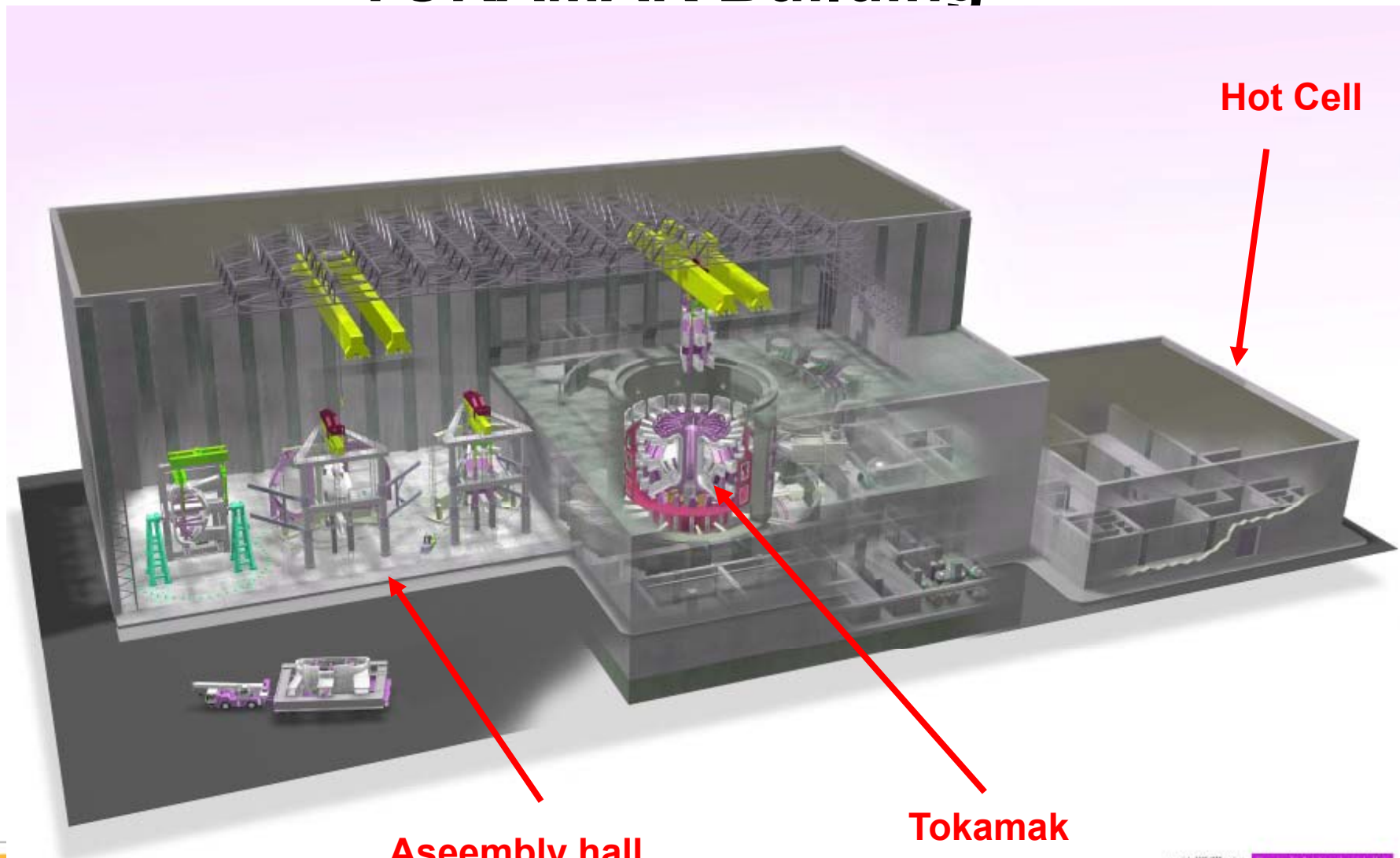
- A unique feature of ITER is that almost all of the machine will be constructed through *in kind* procurement from the Parties



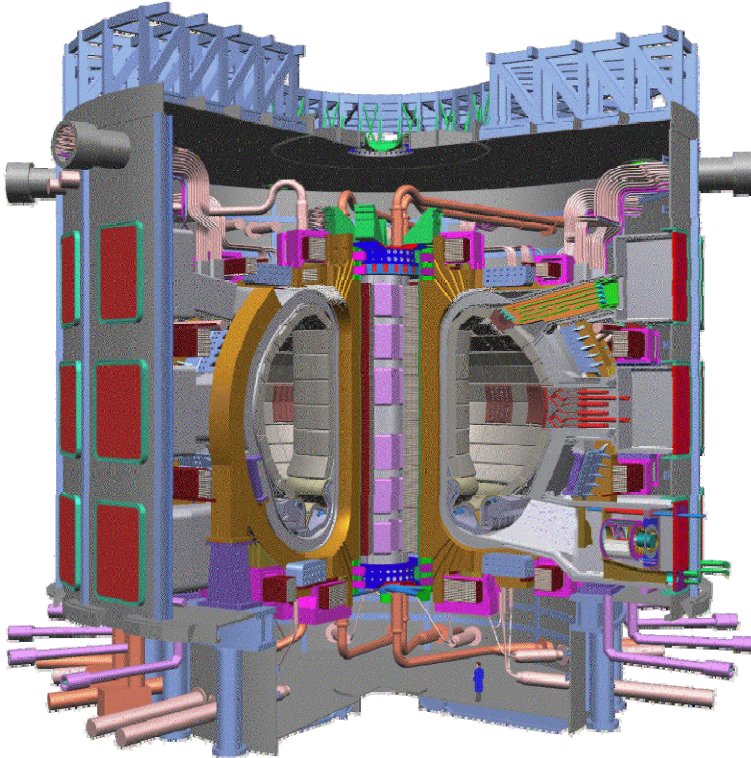
ITER- Buildings and Facilities licensed under French Nuclear Law



TOKAMAK Building



ITER Tokamak – Mass Comparison



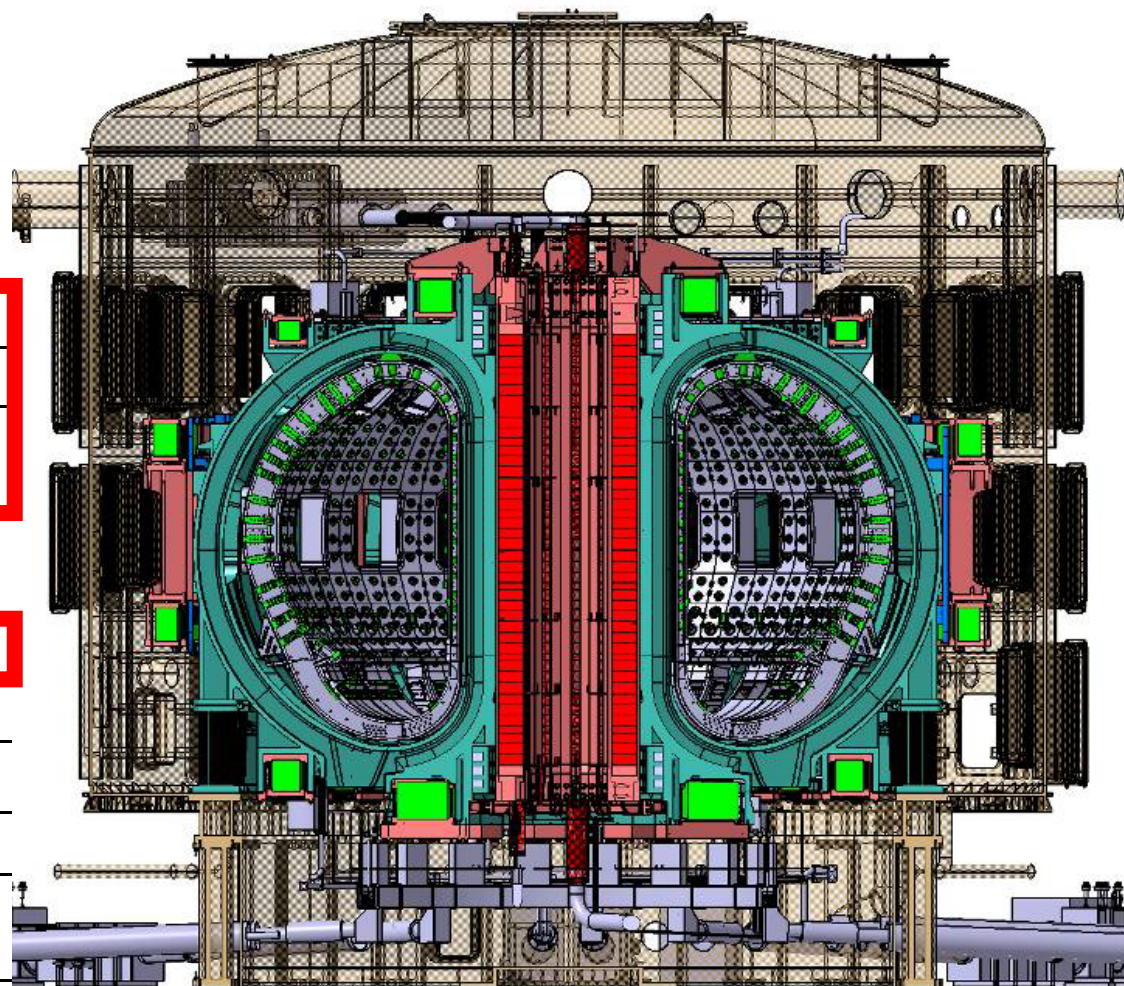
ITER Machine mass:
~23000 t
28 m diameter x 29 m tall



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

The core of ITER

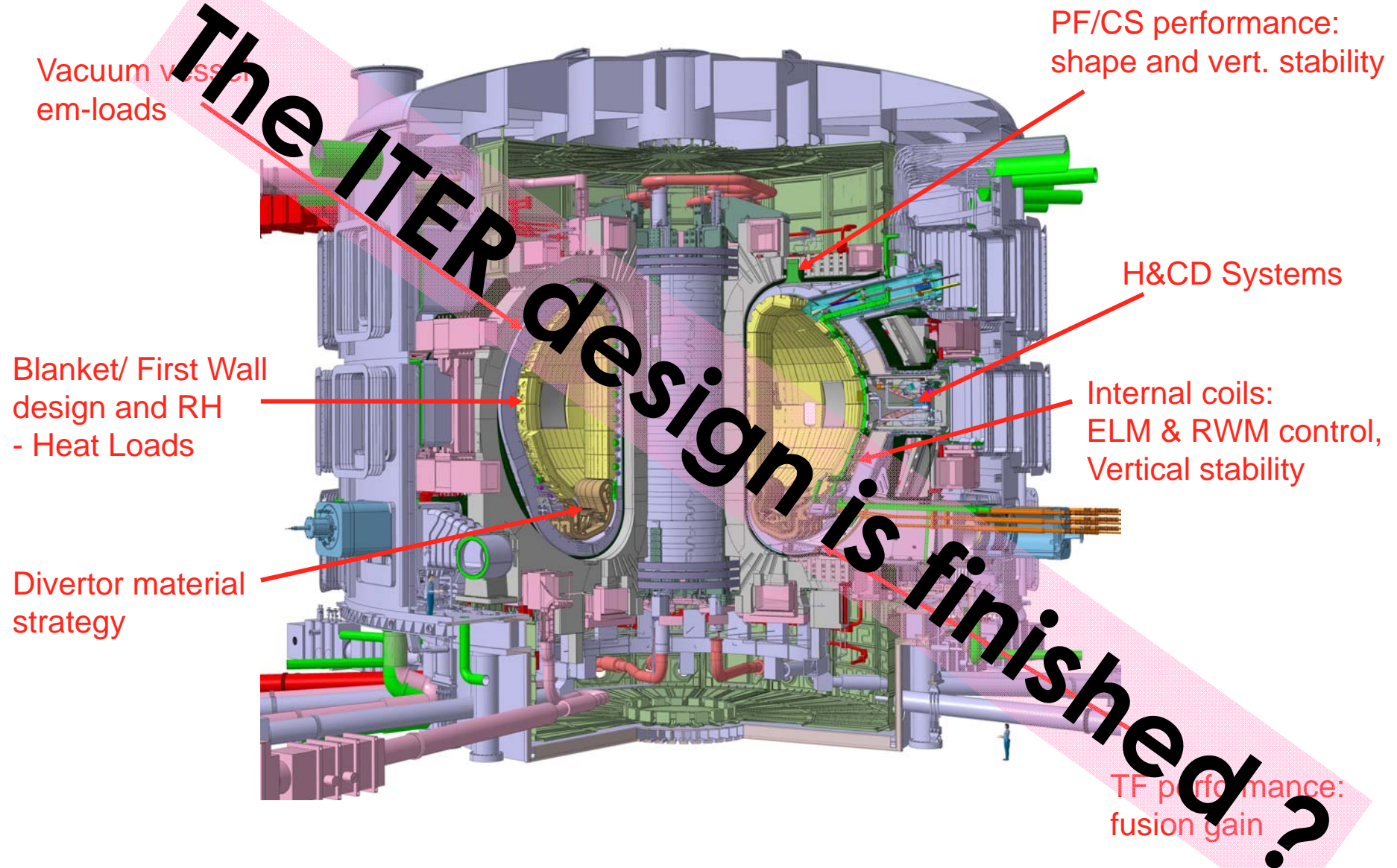
Total fusion power	500 MW
Additional heating power	50 MW
Q - fusion power/ additional heating power	≥ 10
Average 14MeV neutron wall loading	$\geq 0.5 \text{ MW/m}^2$
Plasma inductive burn time	300-500 s *
Plasma major radius (R)	6.2 m
Plasma minor radius (a)	2.0 m
Plasma current (I_p)	15 MA
Toroidal field at 6.2 m radius (B_T)	5.3 T



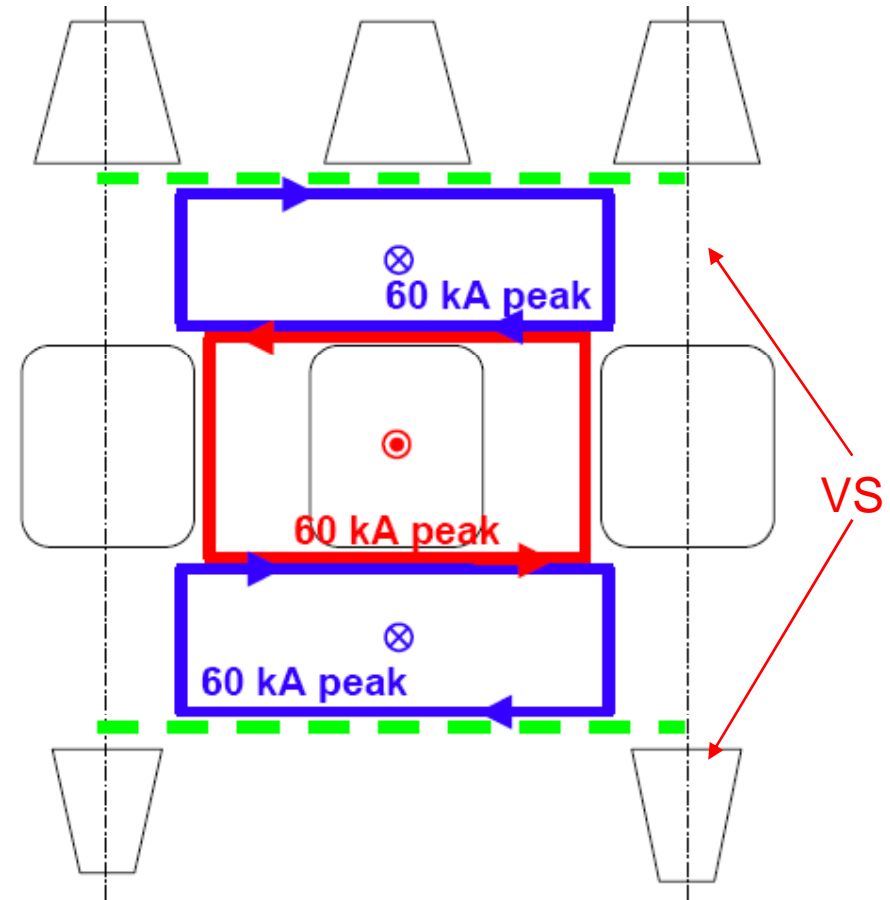
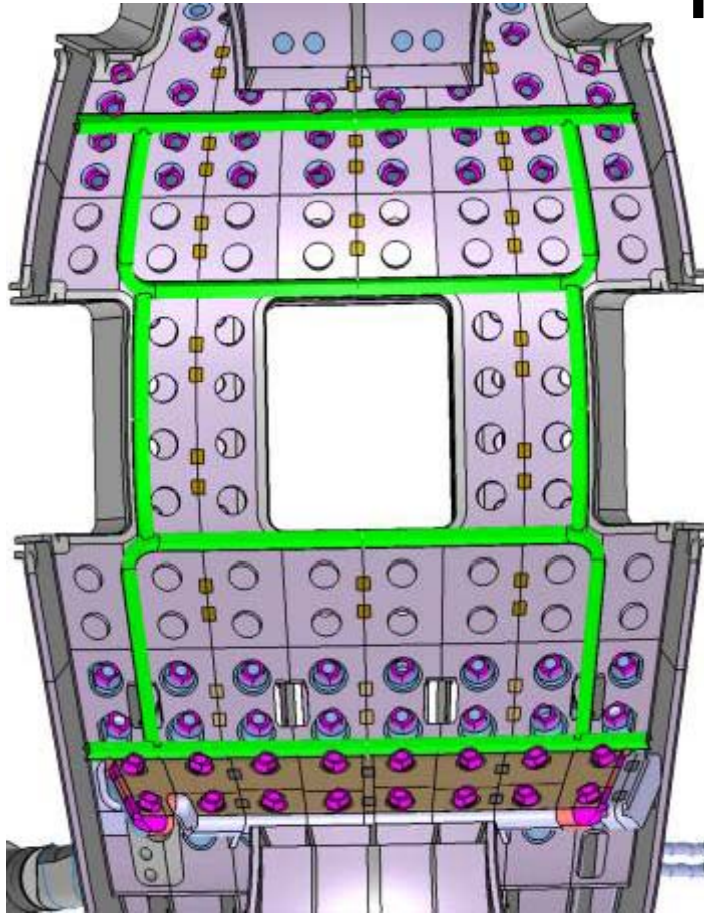
Machine mass: 23350 t (cryostat + VV + magnets)

- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t

Key Design Review Issues - Tokamak

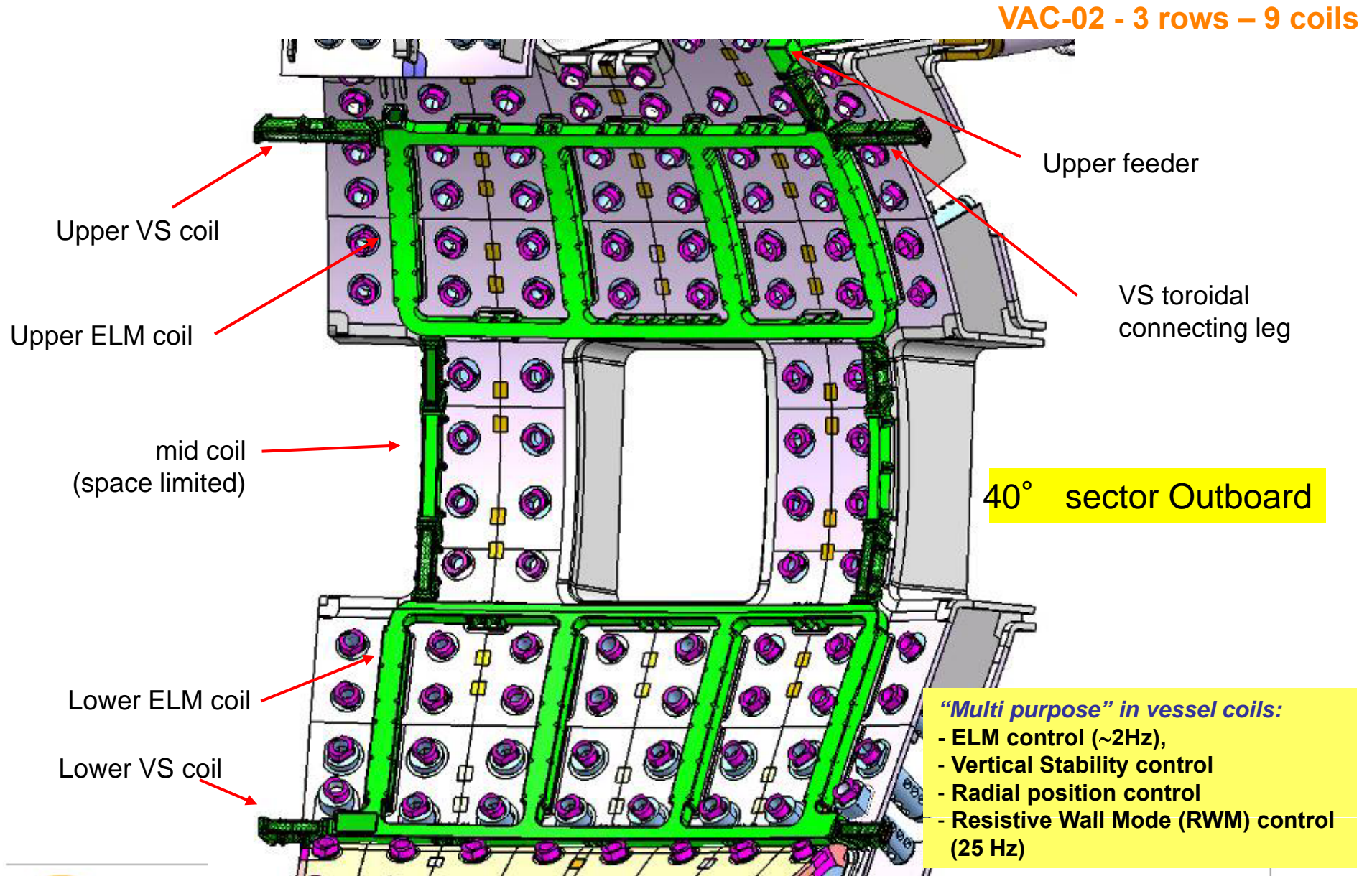


Conceptual: ELM/ VS Control by internal Coils in ITER



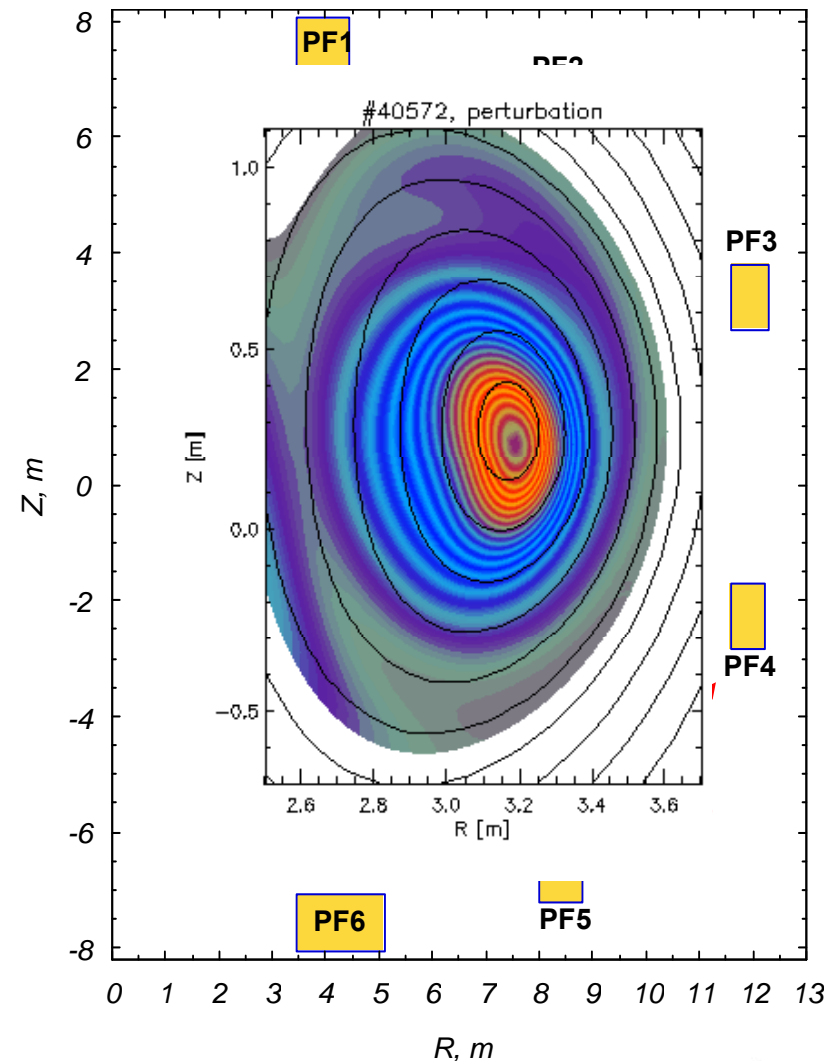
- An internal set of resonant magnetic perturbation (RMP) and vertical stabilization coils under design

ELM & VS coils – layout of reference option

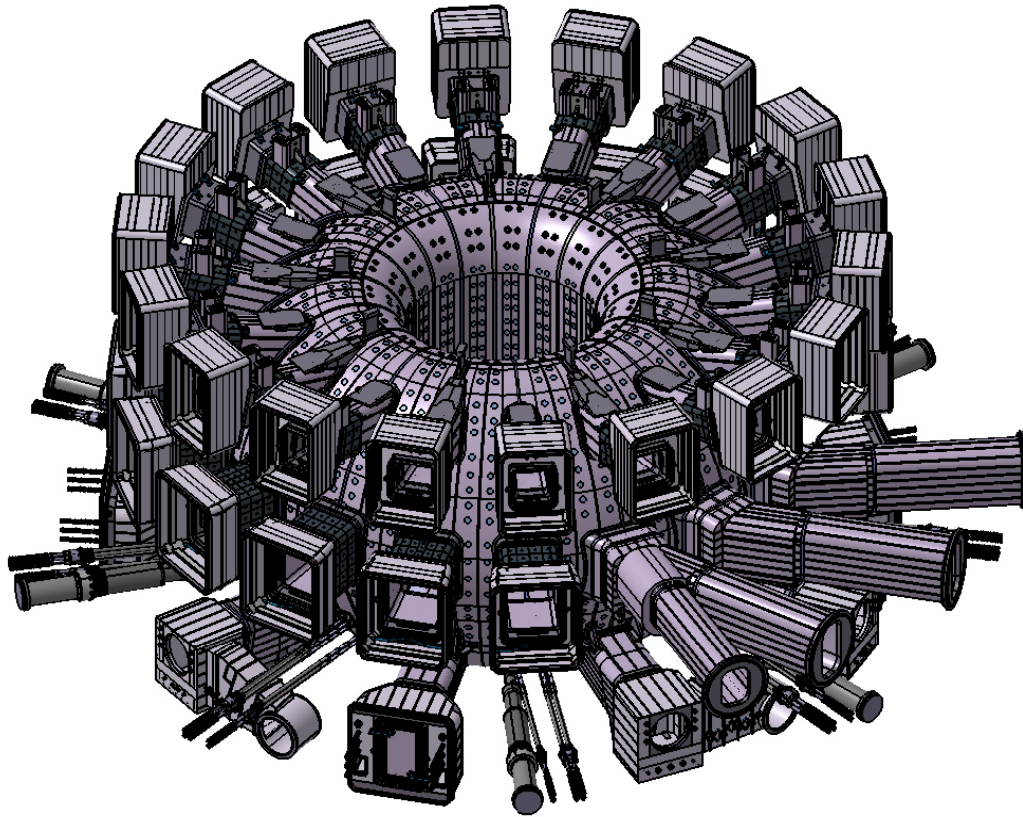


Poloidal Field Control in ITER

- Slow feedback loop through PF coil system:
 - control of plasma current, shape,
 - coil currents, separatrix separation, etc. (5-10 s)
- Fast feedback loop through in vessel coil:
 - stabilization of plasma vertical position (<1 s)
- General Improvements in the PF systems, especially PF6 through increase in current and size



Vacuum Vessel:

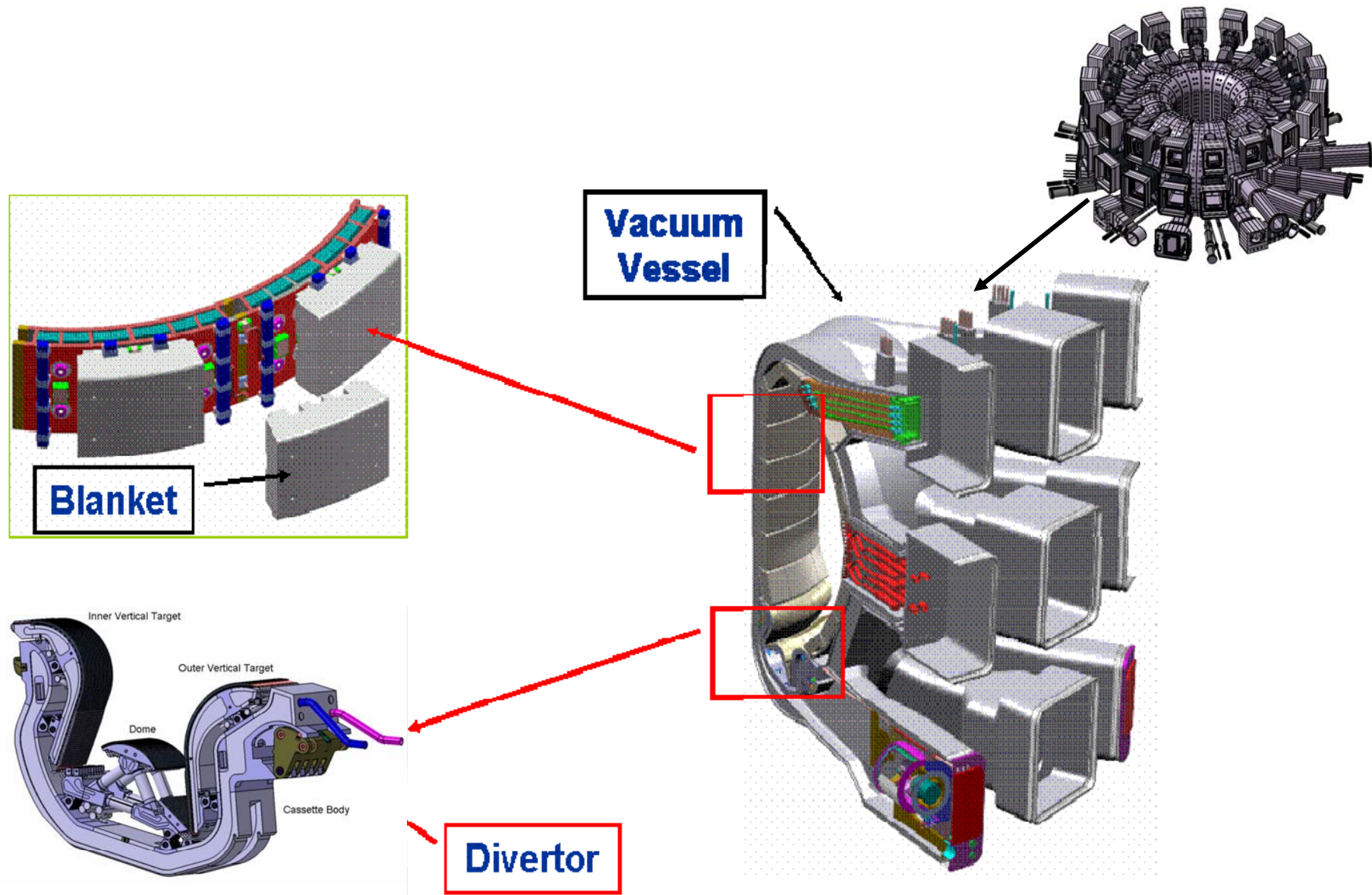


VV & In-vessel components mass: ~8000 t
19.4 m outside diameter x 11.3 m tall

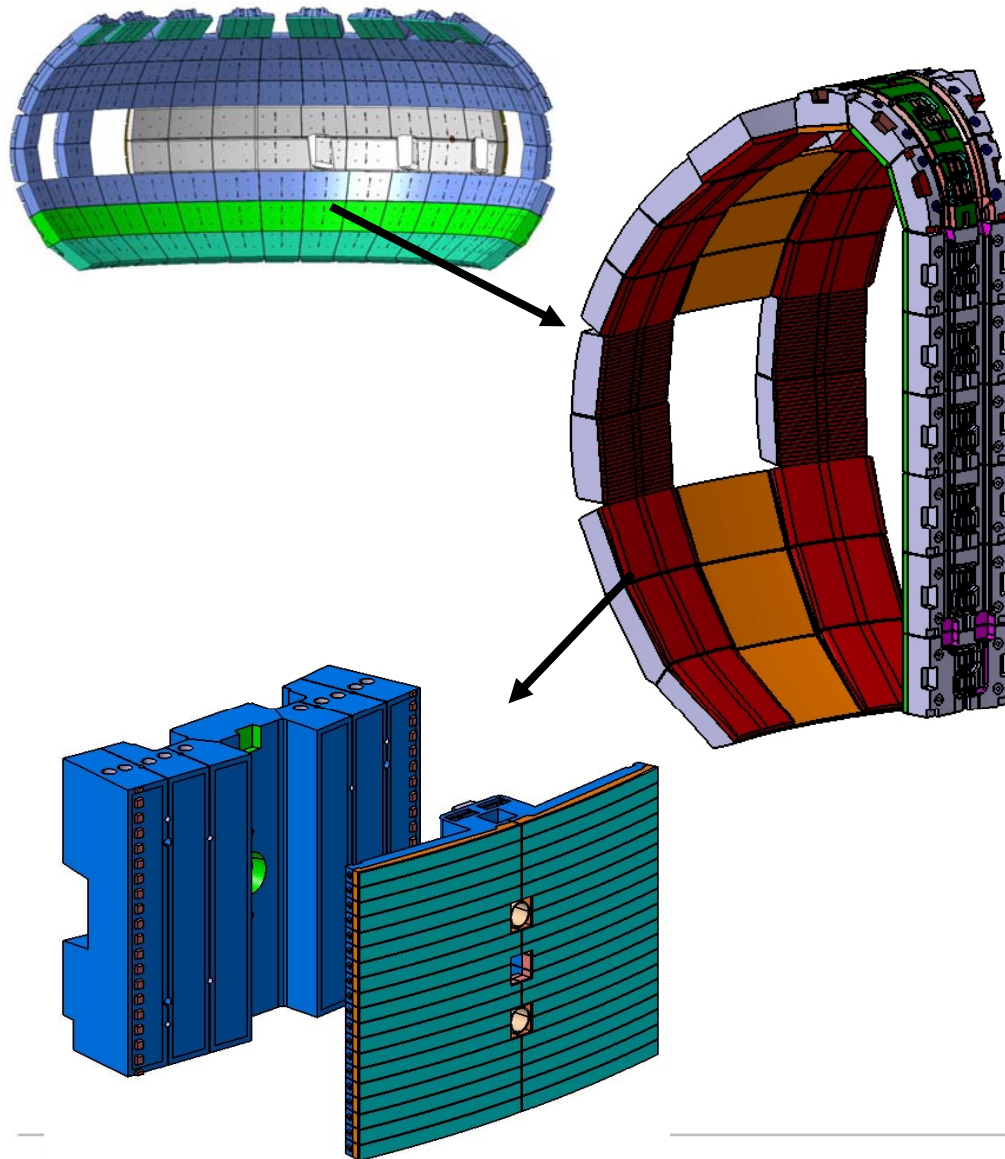


Eiffel Tower mass: ~7300 t
324 m tall
(Completed 1889)

VV and In-vessel Components



Blanket Status & Accomplishments



Status & Accomplishments

- Generic blanket / FW design in progress
- Improved FW shaping in progress (will allow removal of moveable limiters)
- Qualification of mock-ups ongoing with first successful results
- EM analysis benchmarking in progress
- RH design of hydraulic connection in progress
- Thermal & mechanical loads updated and finalized

Overview of the Magnet System

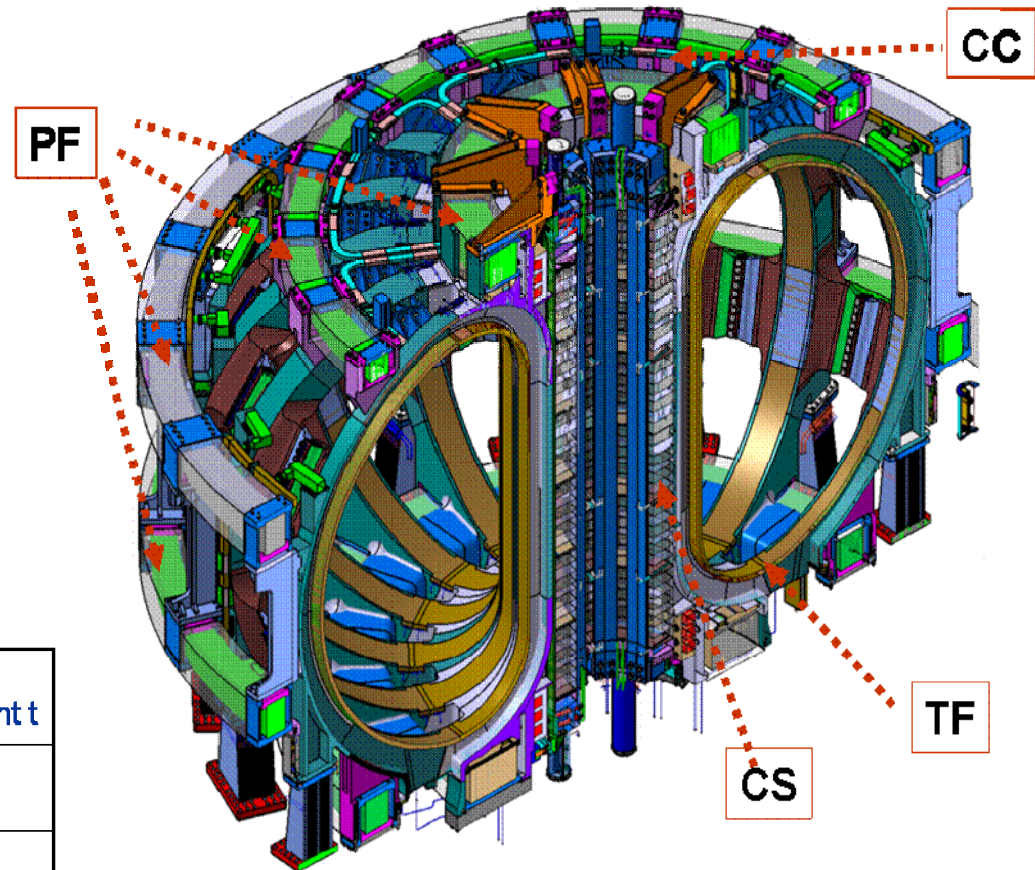
48 superconducting coils

18 TF coils

6 CS modules

6 PF coils

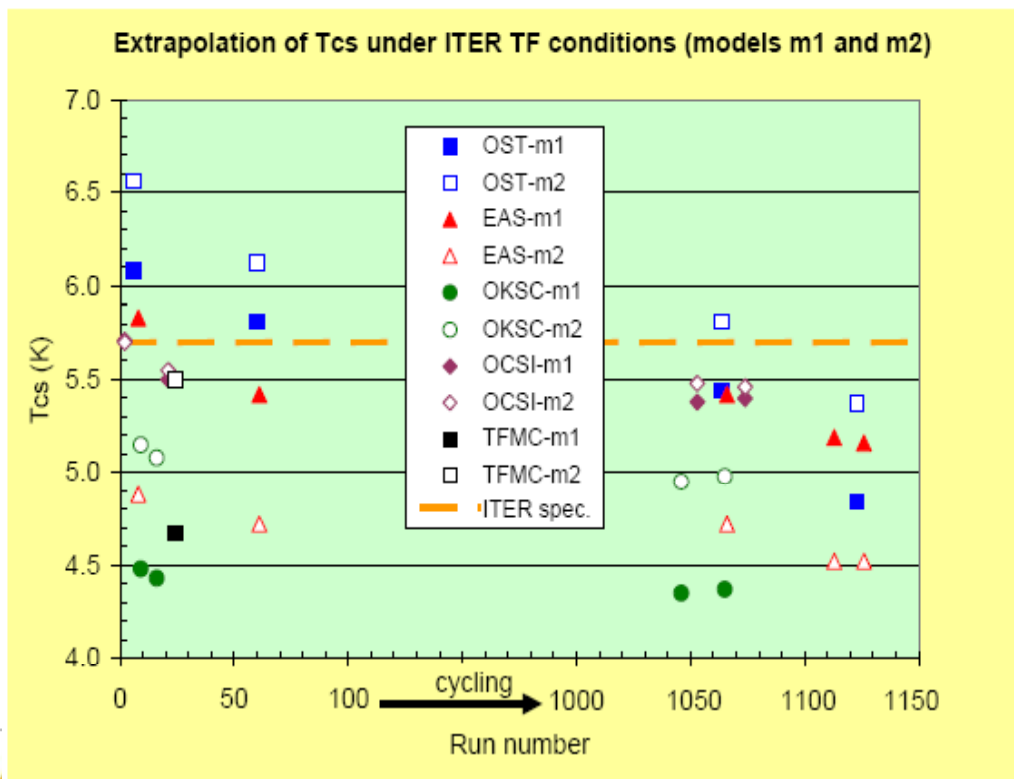
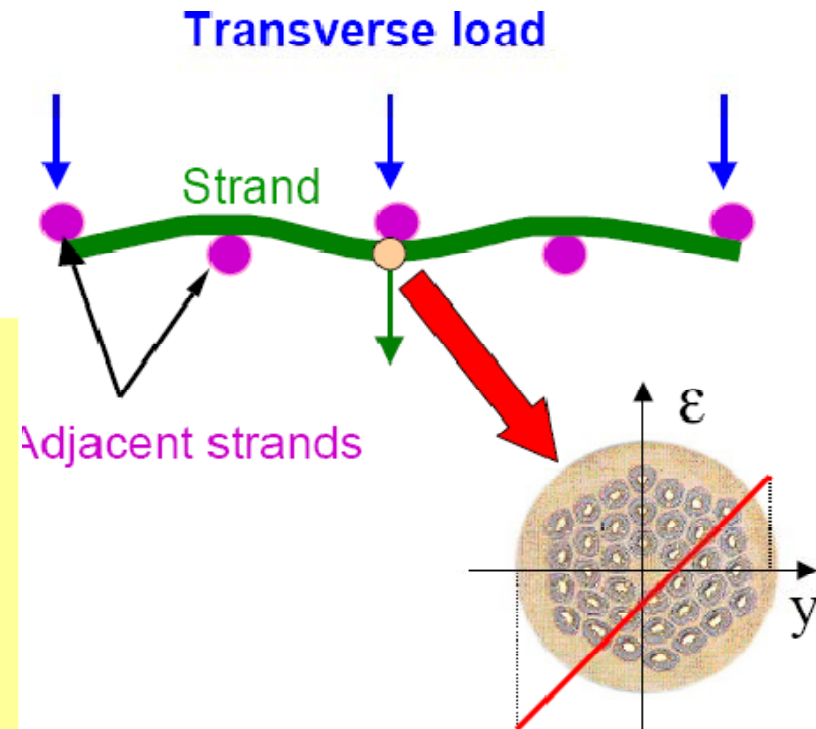
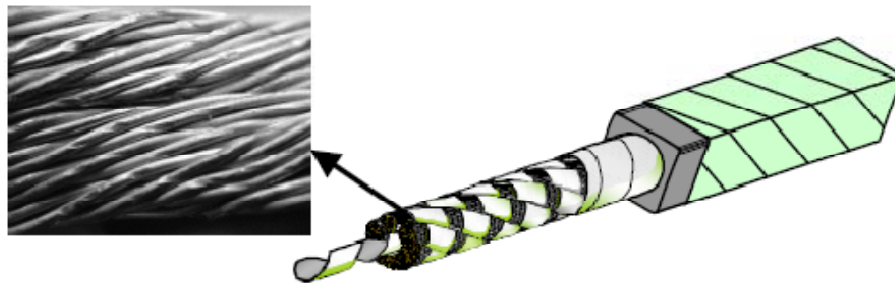
9 pairs of CC



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

Performance Degradation in High Field Magnets

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



Scope of ITER Conductor Supply

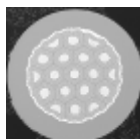
Coil	Total Conductor Length (km)	SC Type	Amount of SC Srrand (t)	Jacket Type	Jacket Material	ITER Credit [kIUA (M€)]	ITER Credit Sharing (%)					
							CN	EU	JA	KO	RF	US
TF	88	Nb ₃ Sn	393	round-in-round	modified 316LN	215 (323)	7.5	20	25	20	20	7.5
CS	62	Nb ₃ Sn	123	round-in-square	JK2LB	90 (135)	-	-	100	-	-	-
PF	42	NbTi	237	round-in-square	316L	81 (122)	65	15	-	-	20	-



TF Conductor



Bronze Nb₃Sn strand developed by EAS, EU



Internal-tin Nb₃Sn strand developed by OST, US



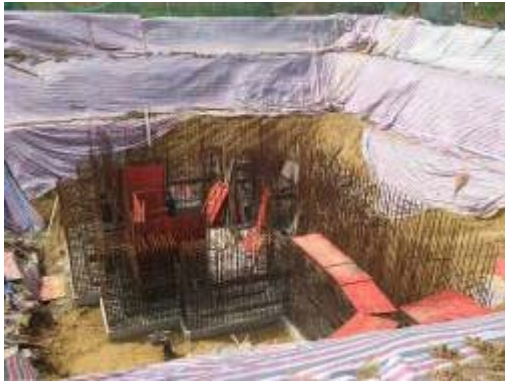
PF Conductor



NbTi strand developed by VNIINM, RF

Jacketing Lines

- Longest lead item is the setting up of **jacketing lines**.



(Courtesy of
Wu Yu, ASIPP)



Civil Engineering Work at ASIPP, CN (TF & PF)



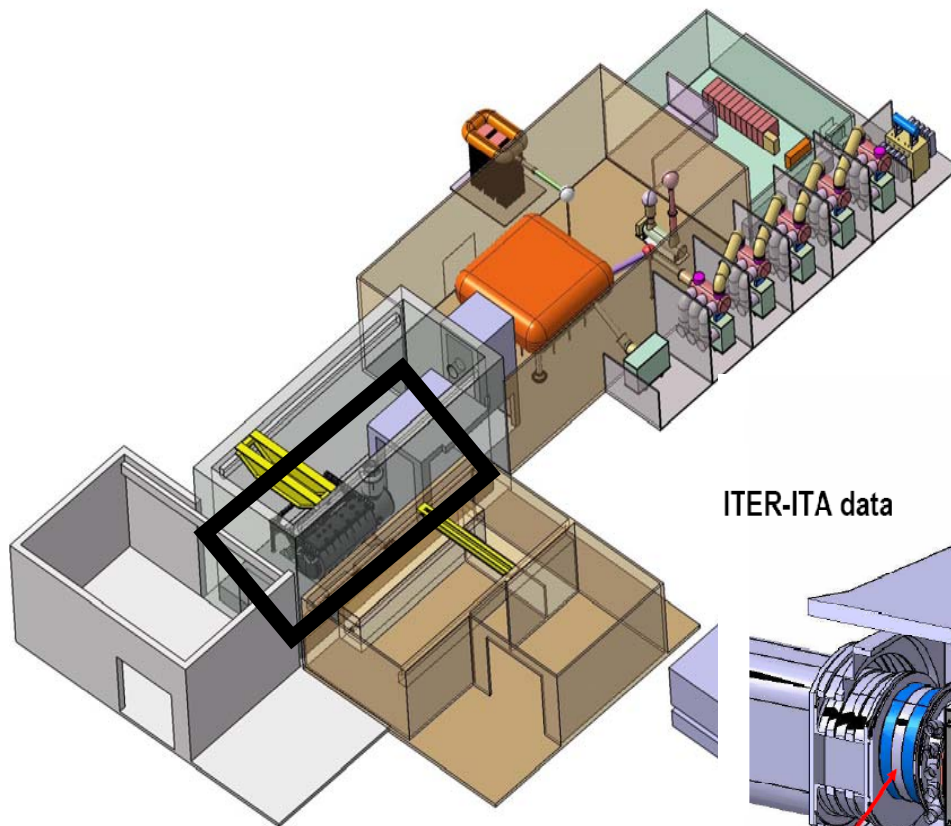
(Courtesy of
A. Taran,
VNIKP)



Civil Engineering Work at UNK under VNIKP Supervision, RF (TF)

ITERs accelerator !

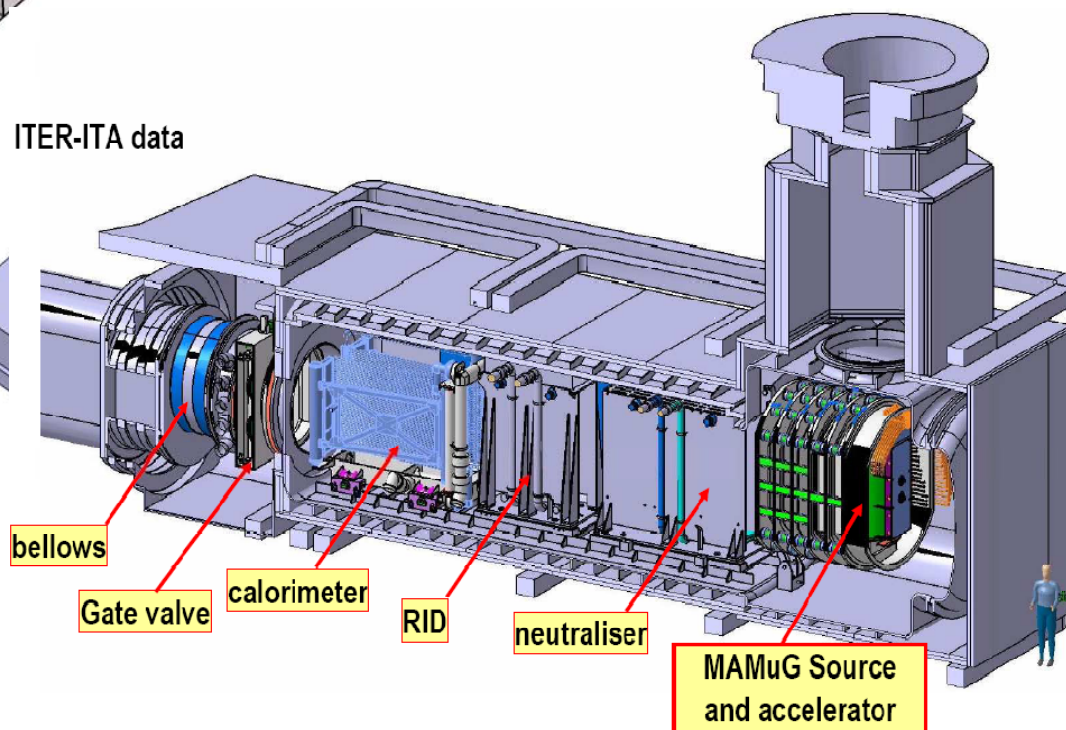
The NB test facility in Padua



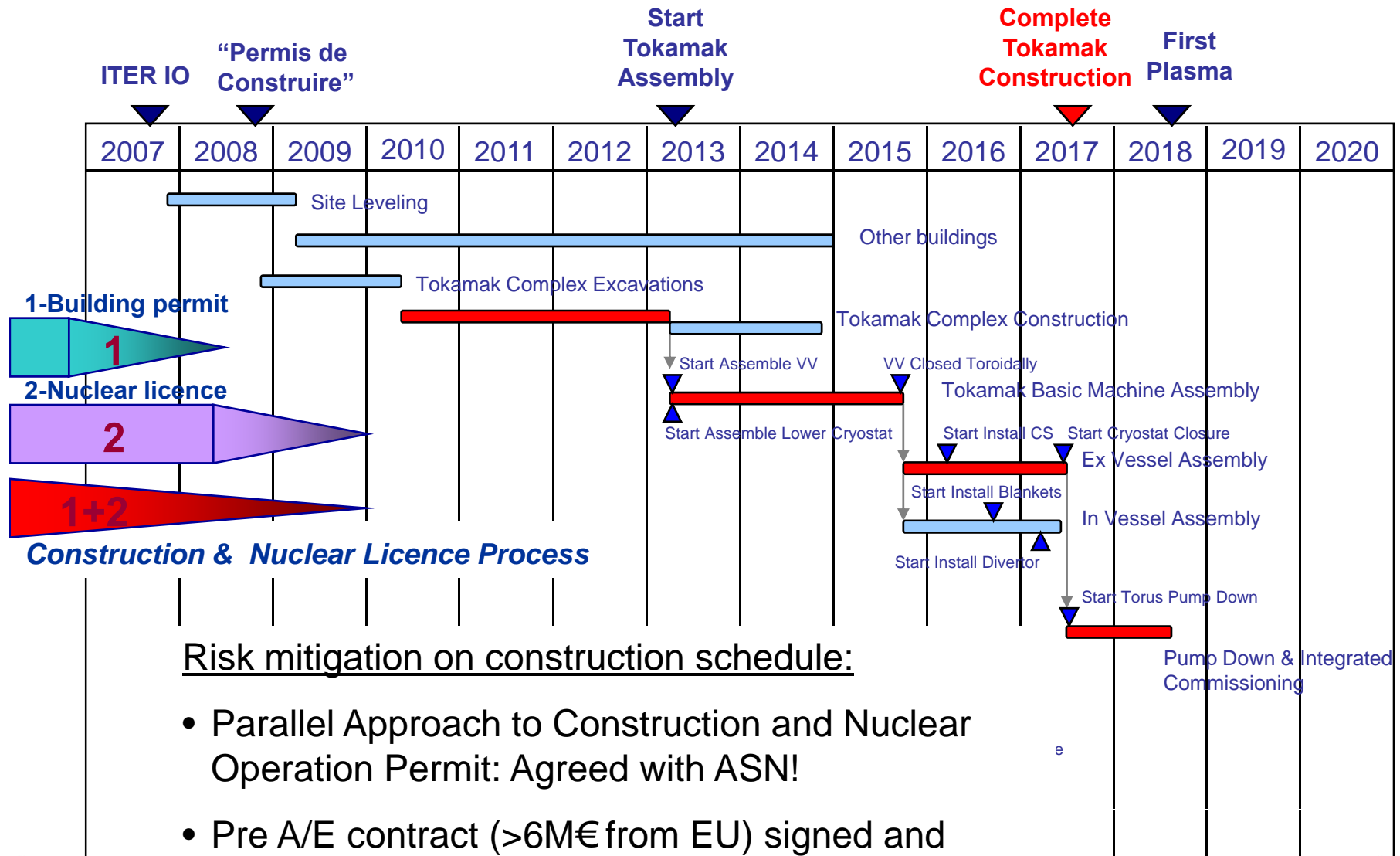
Neutral Beam Test Facility

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

ITER-ITA data



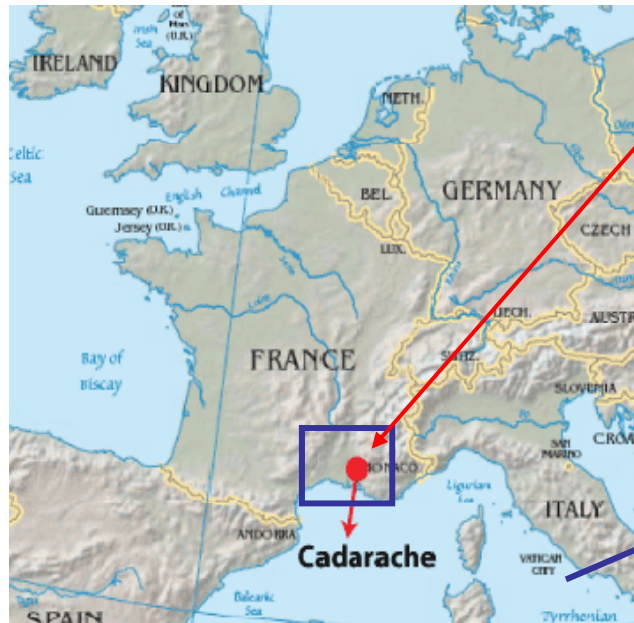
The Schedule



ITER Construction Site / AIF



Itinerary of ITER Components



ITER Site

— = Itinerary of ITER Components



Office Buildings

CEA site



JWS-1: Building 519



Extension-1



Extension-2

ITER site

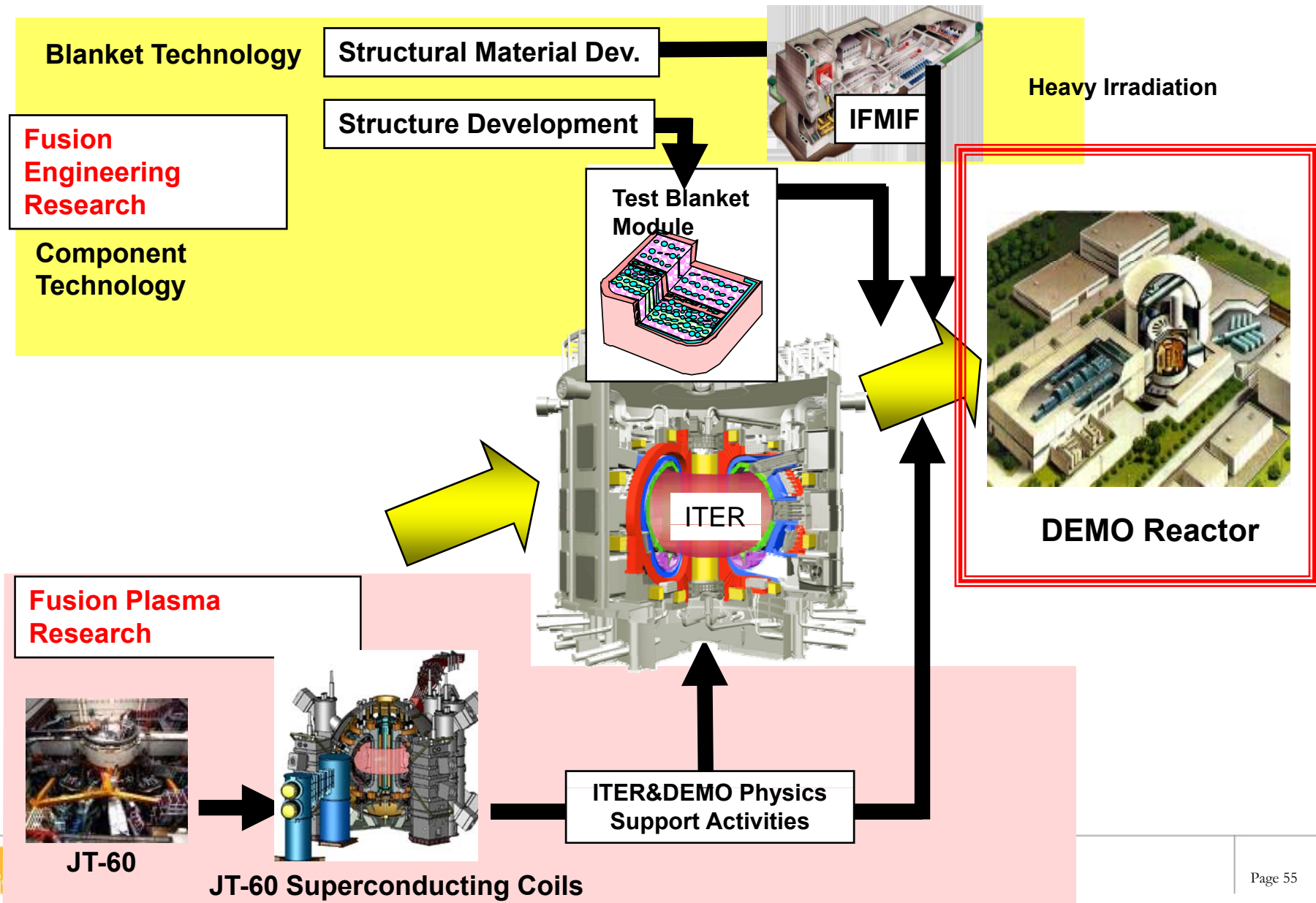


JWS-2



Future Annex Office Building

Materials: The outstanding question !

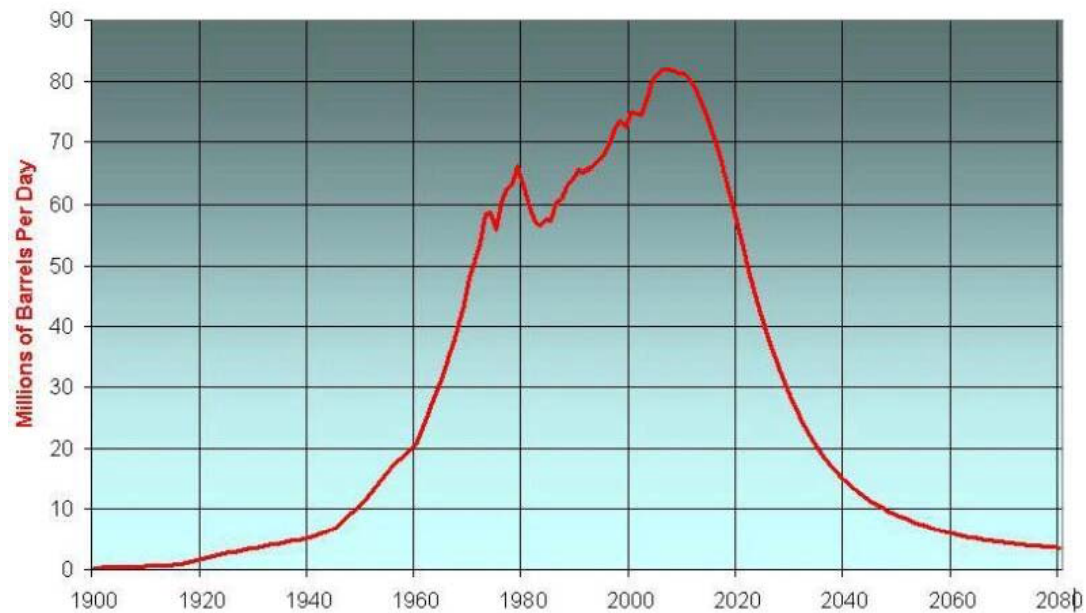


What if ITER can not?

- $Q > 10$ sustained operation is not possible
 - Material development will not produce sustainable maintenance strategy
 - Substantial heating system will be required with low efficiency (overall efficiency is too low!!!)
1. Nuclear fusion based on Tokamaks is not to be further developed as a direct energy source
 2. Stellarator technology will need to be pushed much harder
 3. There is another possibility..... The hybrid
http://en.wikipedia.org/wiki/Hybrid_nuclear_fusion

ITER – a Global Challenge

World Oil Production 1900-2080



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

Summary

- **ITER is a tremendous technical, managerial and scientific adventure exploring and pushing forward the frontiers of our knowledge.**
 - **All available sources of energy will be required, but Nuclear Energy will have to be part of the world energy mix... its just a question of time.**
 - **Technology developed for Fusion could provide a contribution to the greatest challenge to mankind.**
 - **ITER is the spearhead for that approach.**
- 