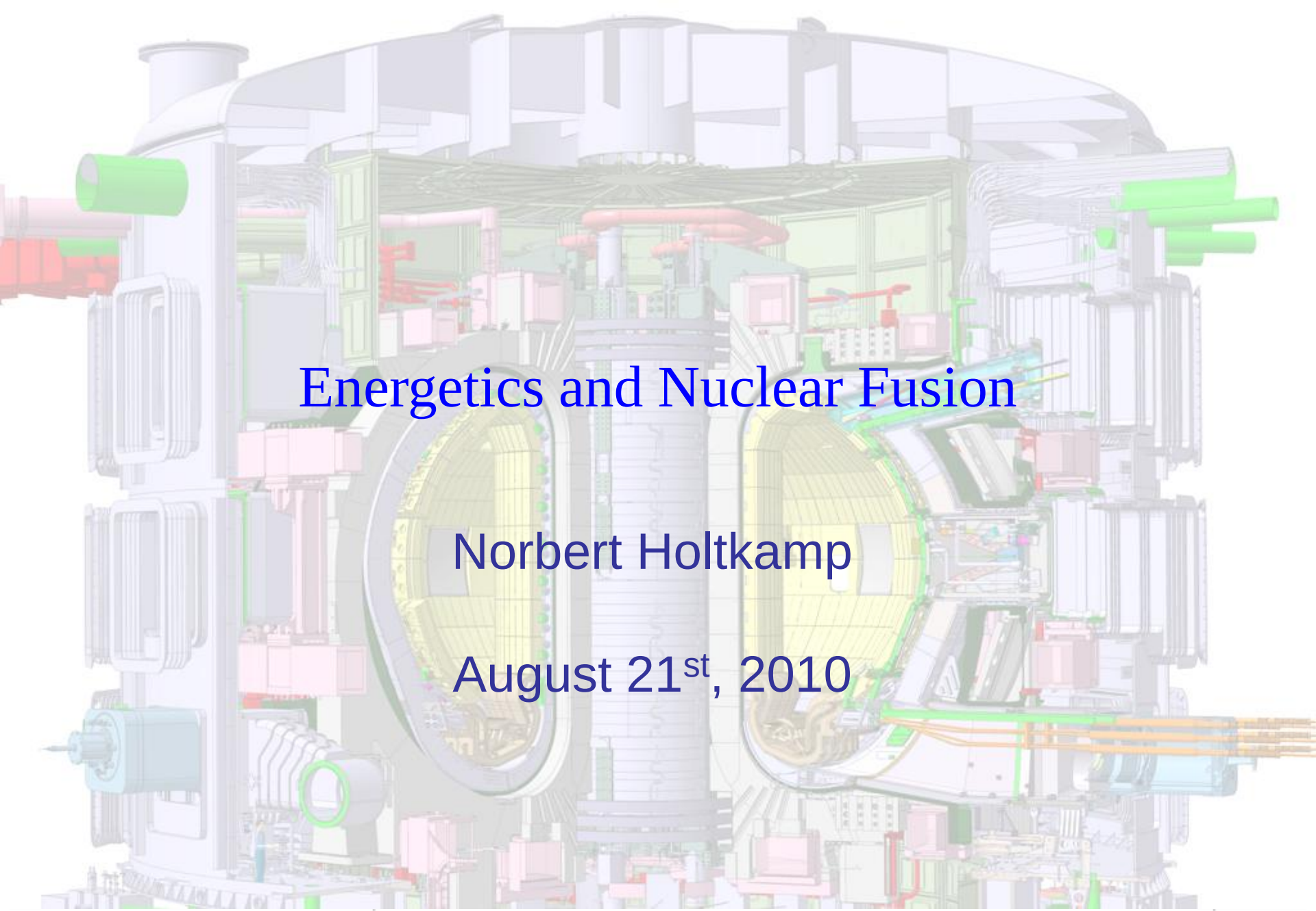


Energetics and Nuclear Fusion

Norbert Holtkamp

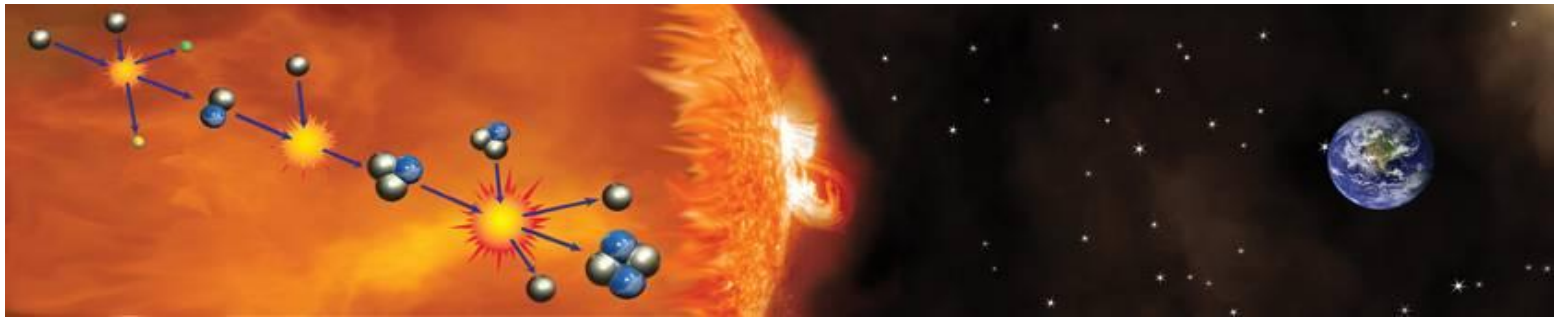
August 21st, 2010

Norbert Holtkamp

- *born Nov. 23, 1961*
- *Studied Physics in Berlin, Darmstadt und Stanford ('82-'88,'89-'91,'91); PhD at TU Darmstadt 1990*
- *DESY '92-'98*
  - *–Linear Collider*
- *FERMI National Accelerator Lab, '98-'00*
  - *–Muon Collider / Neutrino Factory*
- *Oak Ridge National Lab, Jan '01- Aug ’06*
  - *–Spallation Neutron Source*
- *ITER, Principal Deputy Director General, April 2006*
  - *–500 MW Tokamak*
- *Married, two children (19, 22)*

Fusion powers the sun and the stars

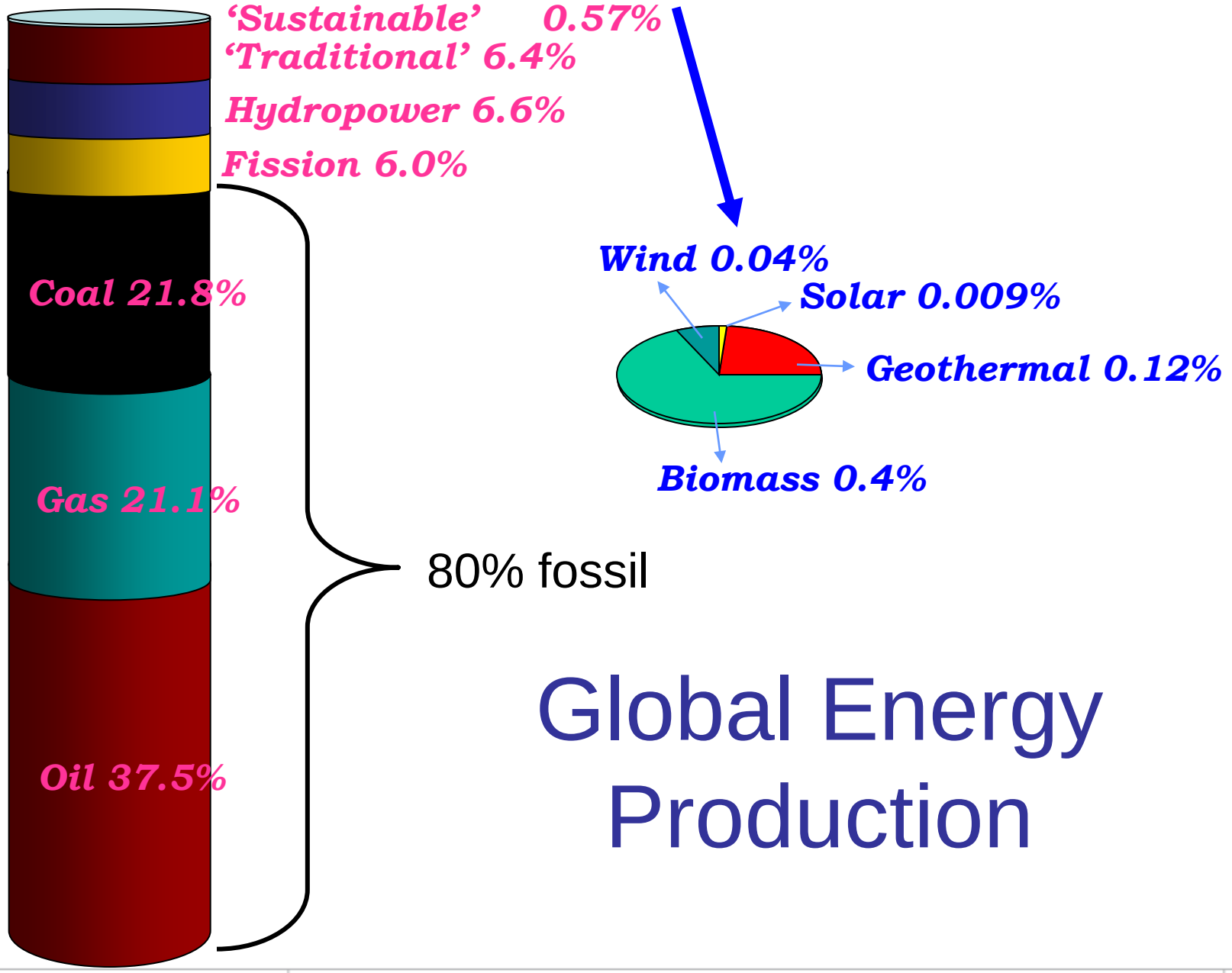
"…Prometheus stole the fire from the heaven"



On Earth,

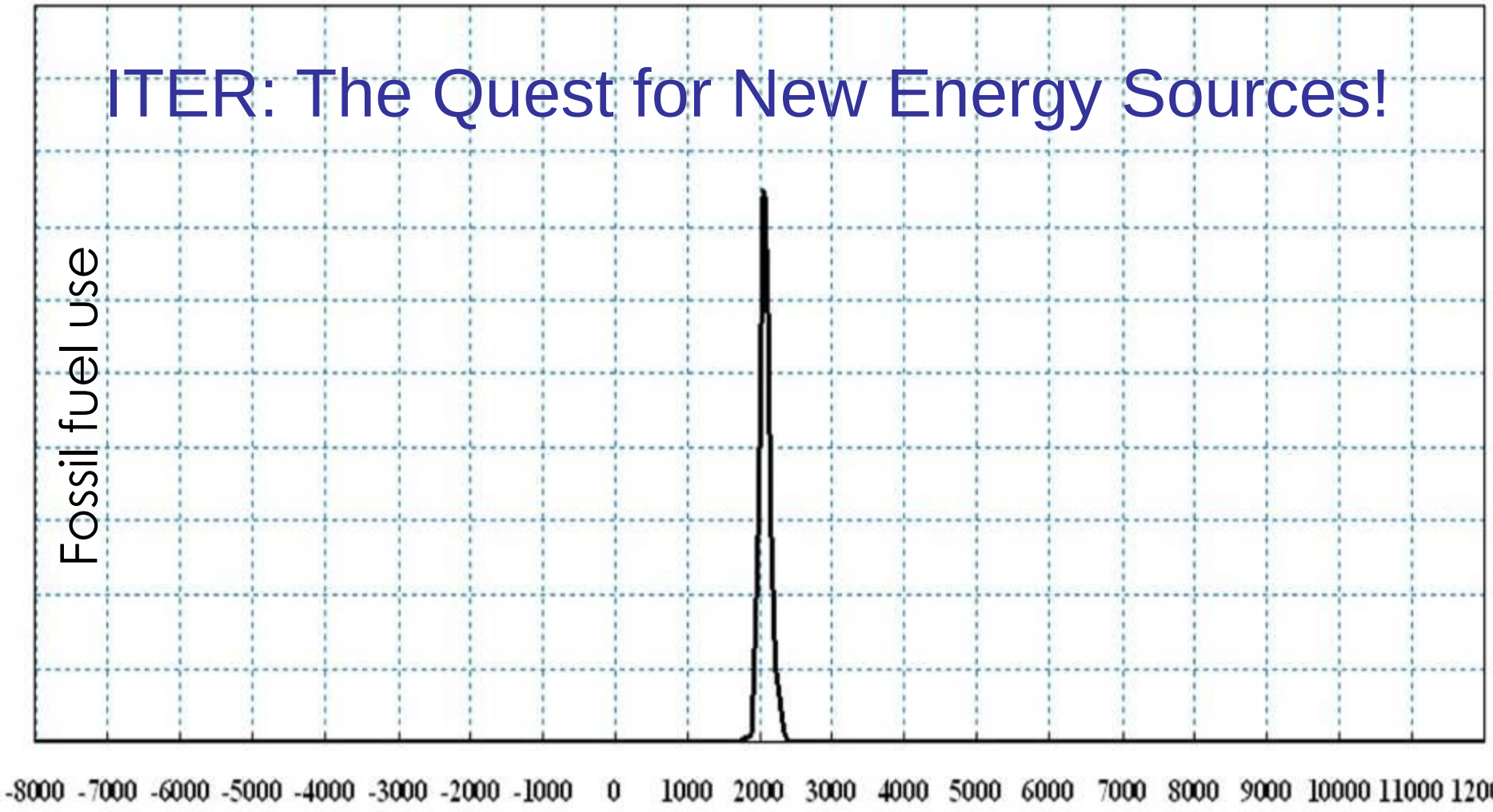
fusion could provide:

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



Global Energy Production

ITER: The Quest for New Energy Sources!

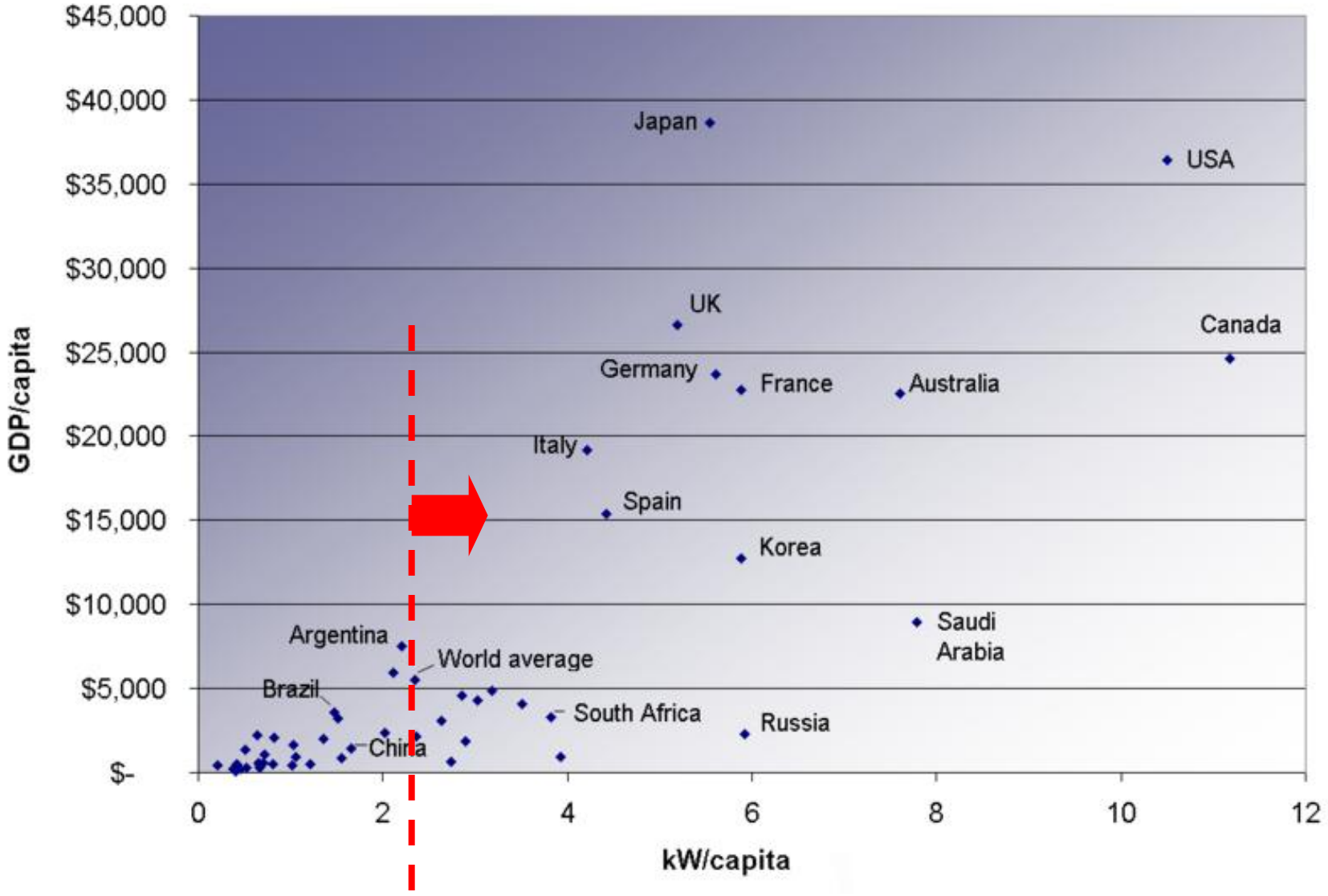


Fossil Fuel Use

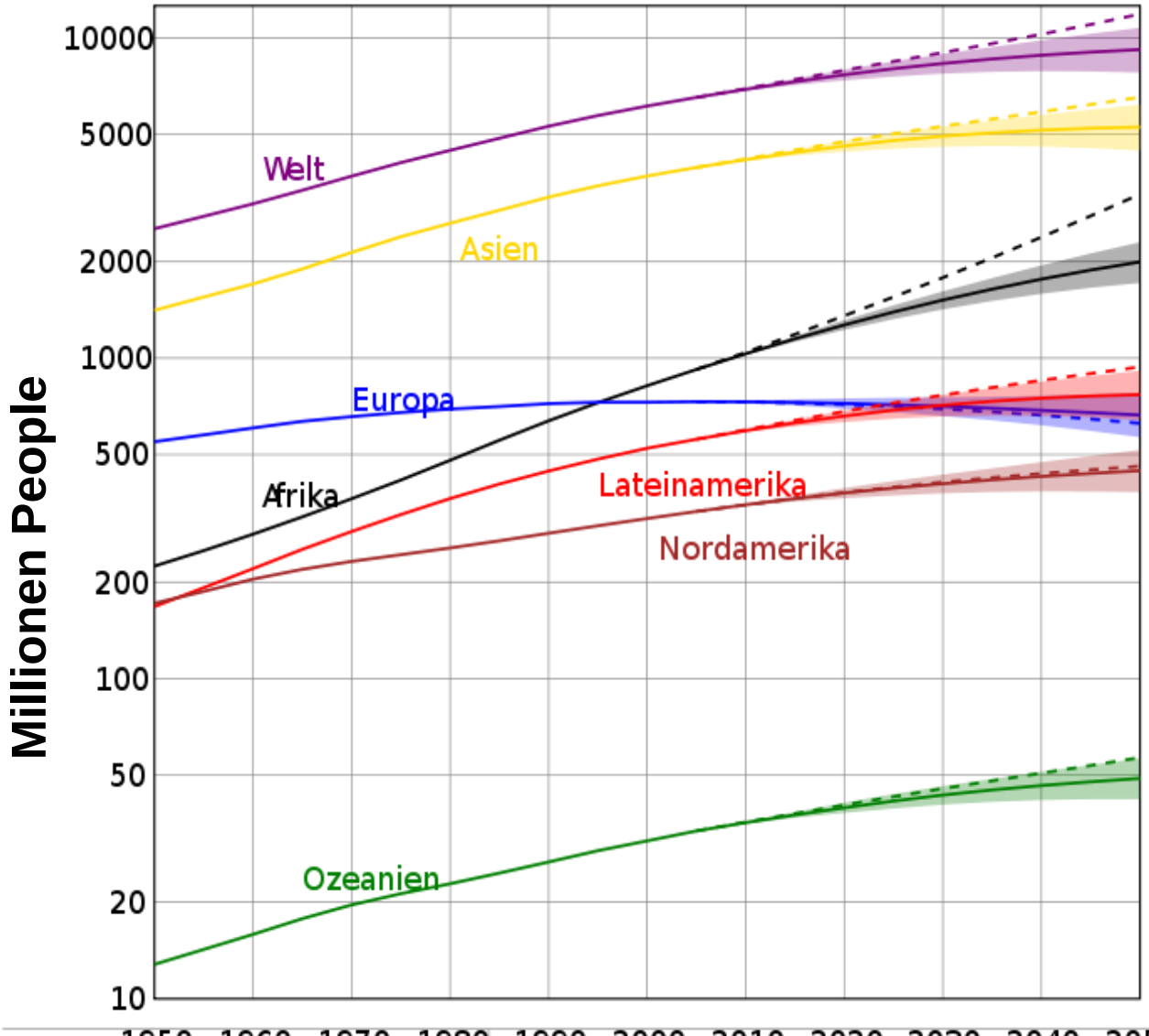
a brief episode in the world's history

View from a High Energy Physics Theorist: C.L. Smith

The Energy Dilemma



Population Growth



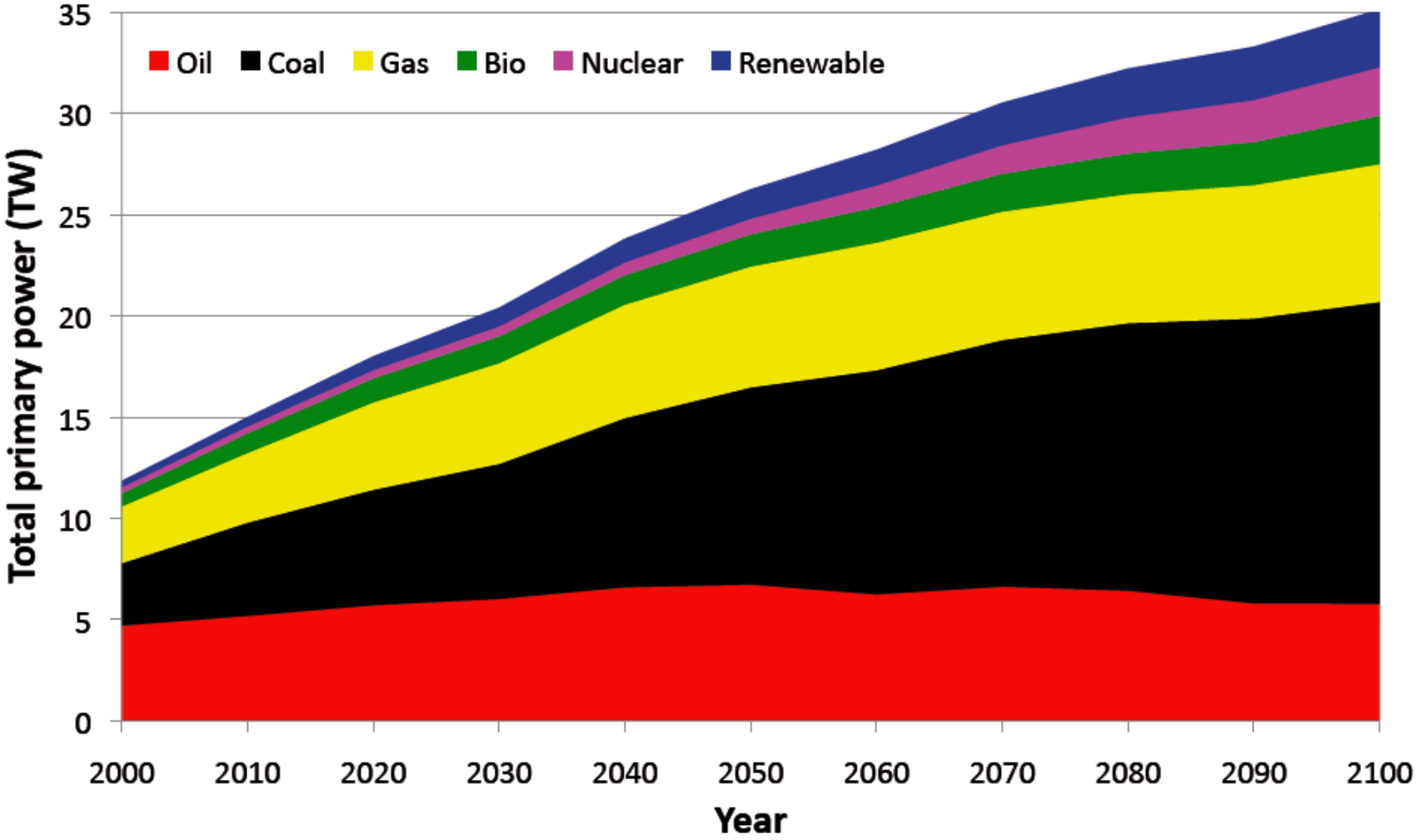
Growth in developing countries

Stagnation or reduction in developed countries

10 Billion people with 3 kW/Kopf will need 30 Terawatt (TW) !

~ 12 TW Electricity

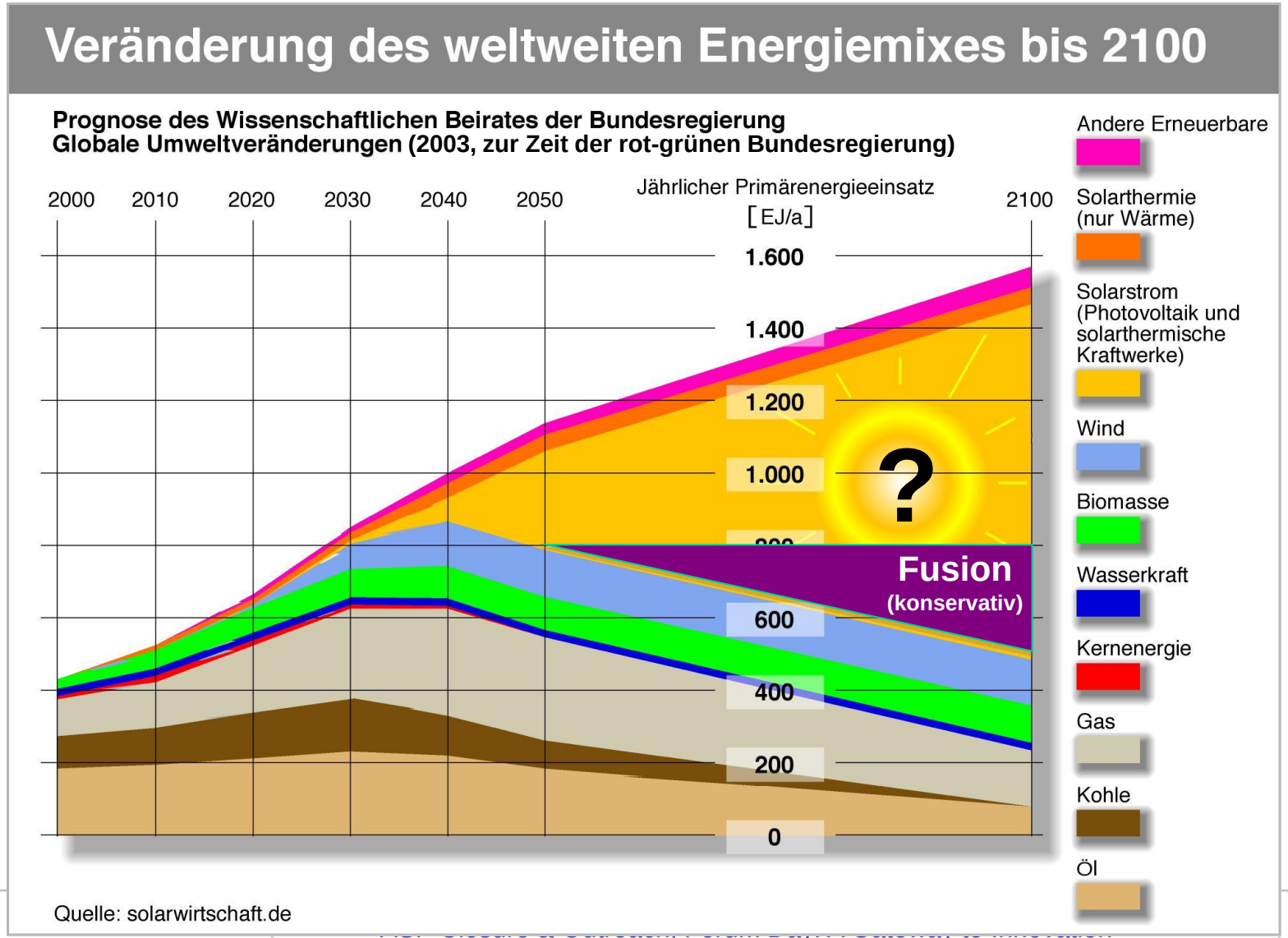
„Business as usual“ Scenario



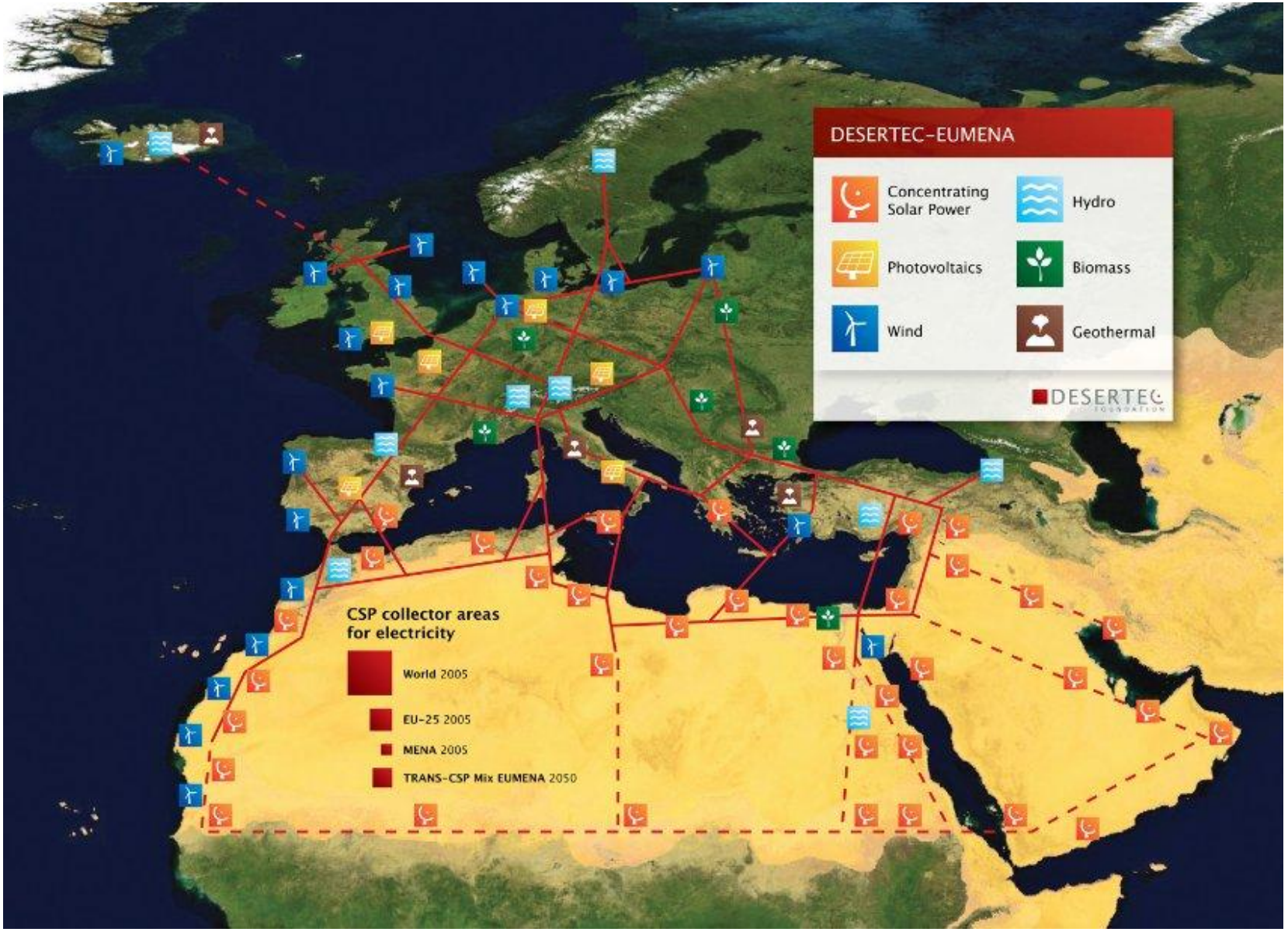
➔**Will need ~8000 new Coal fired plants = ca. 2 per week until 2100 with an estimated 4-6° C global temperature increase**

Clarke, Edmonds, Krey, Richels, Rose, Tavoni; Energy Economics 31, S64 (2009)

The Solar Society?

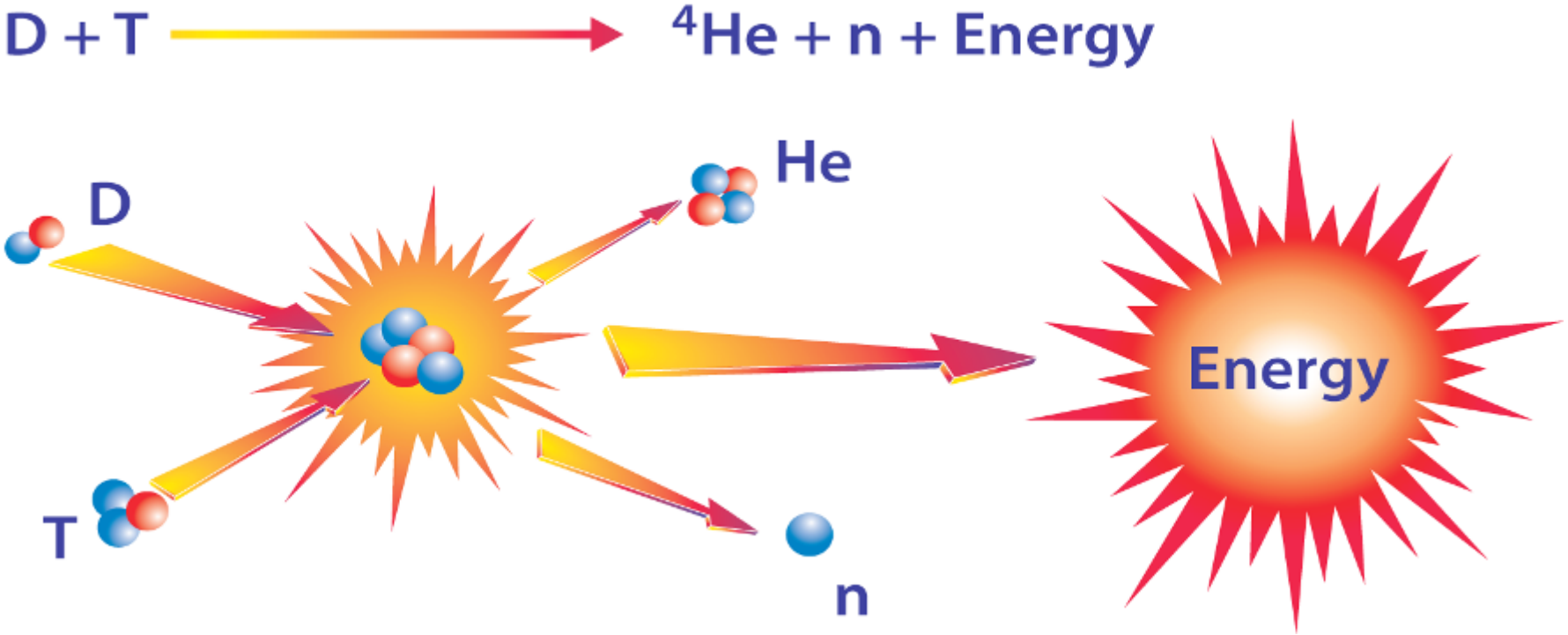


High Voltage DC distribution

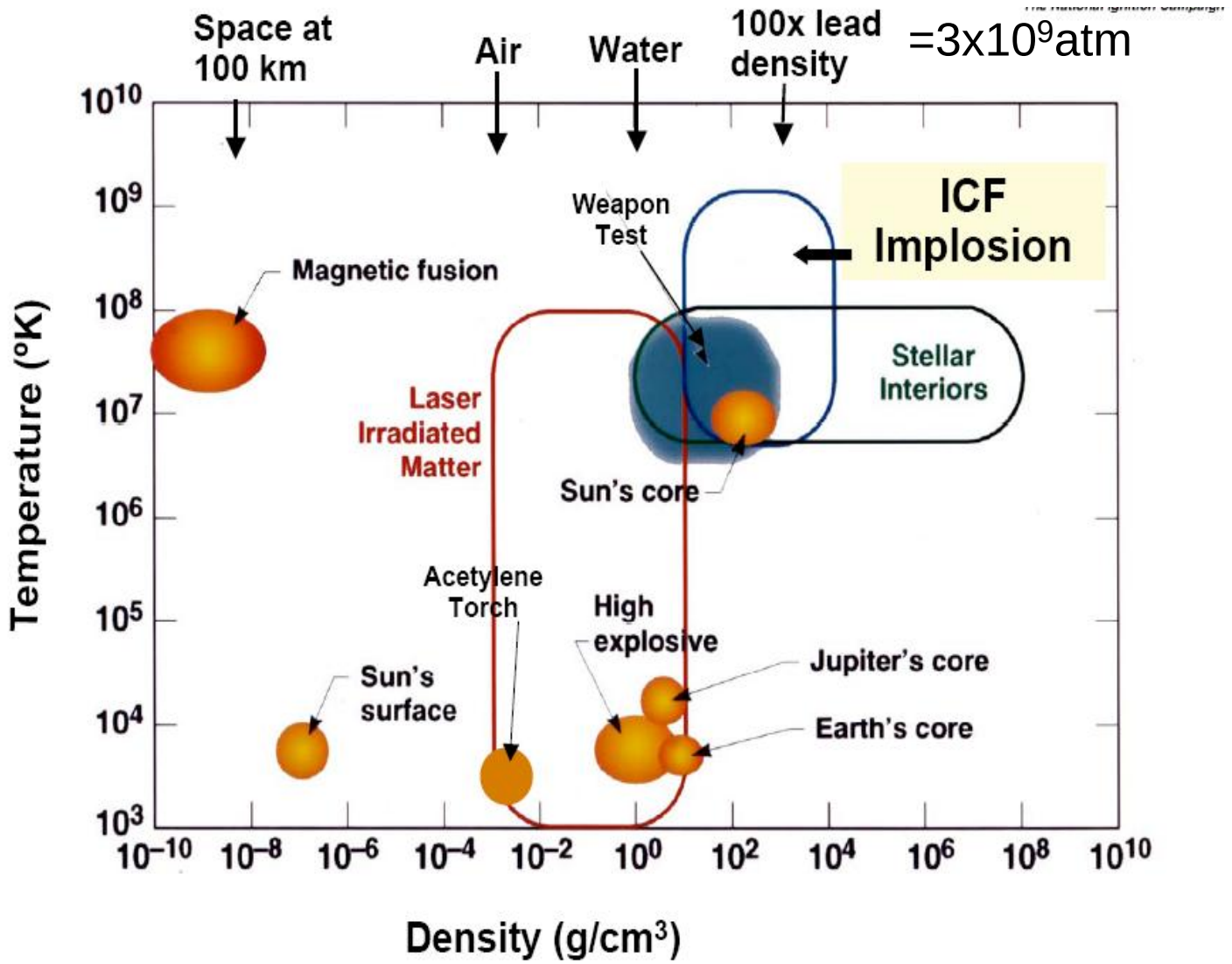


The Fusion Reaction on Earth

"... is not the same as in the Sun"



Fusion in the Universe



+

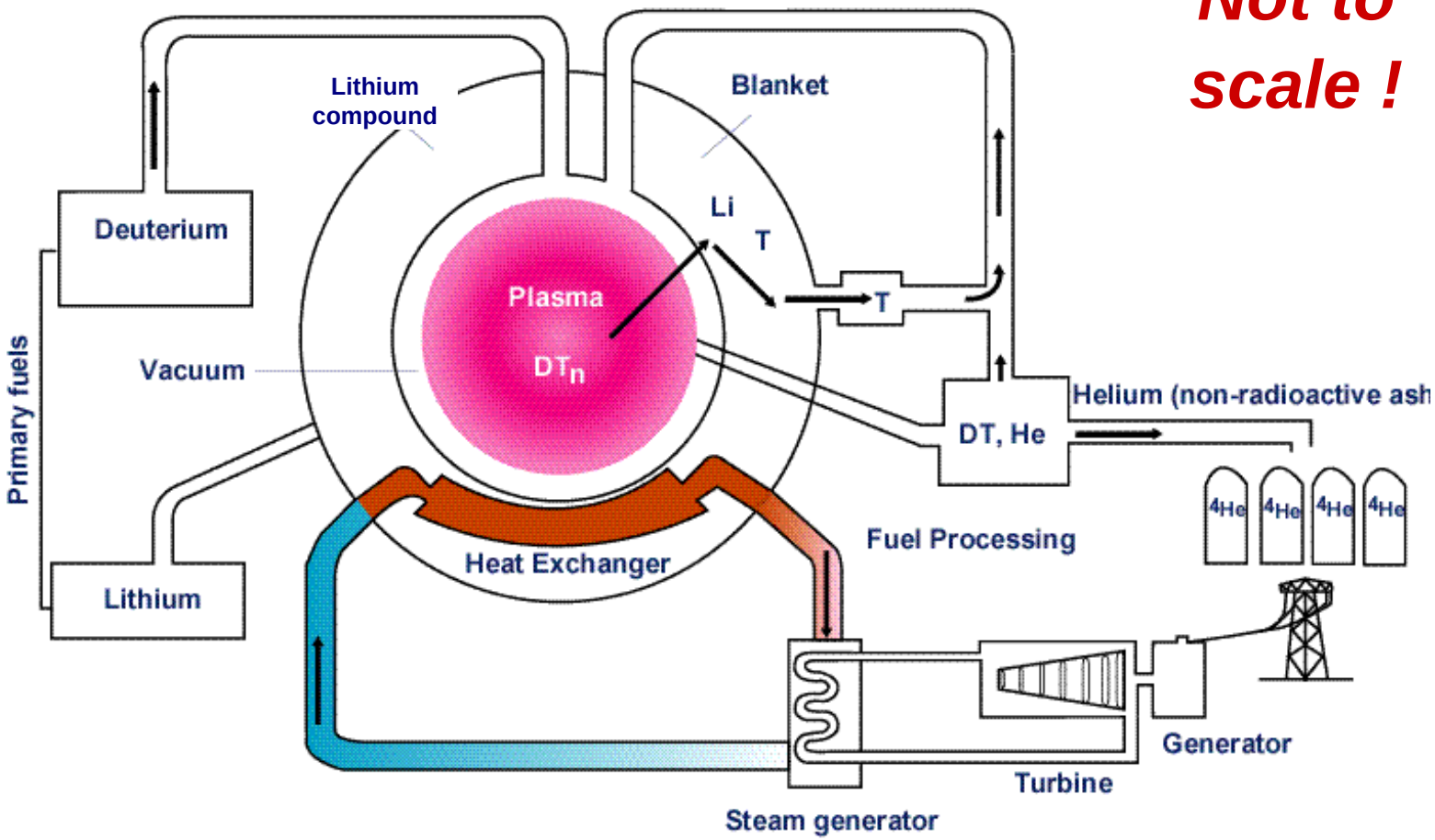
= Energy

- Take the lithium from the battery of a single laptop computer, add half a bathtub of water, and it can give you 200,000 kilowatt hours of electricity

- That's enough to power one person in the UK for 30 years, including their share of industrial electricity.

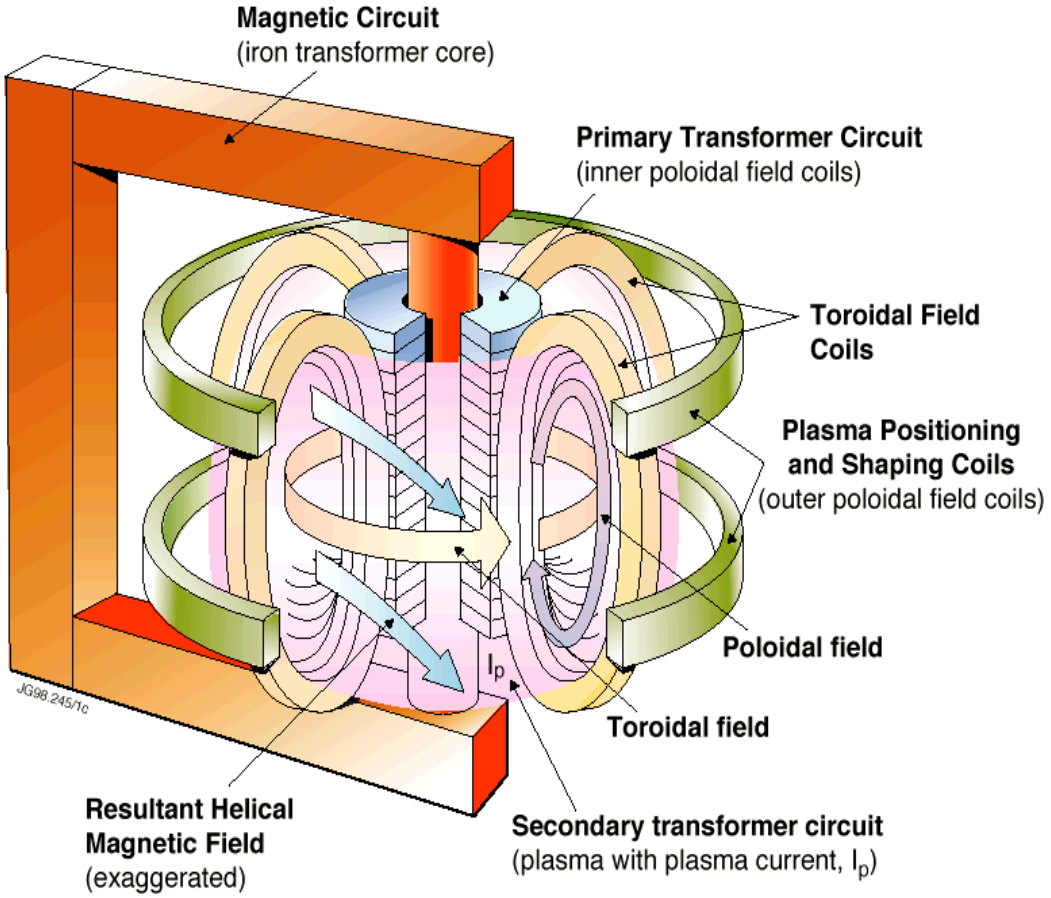
A Fusion power plant would work like that…

Not to scale !



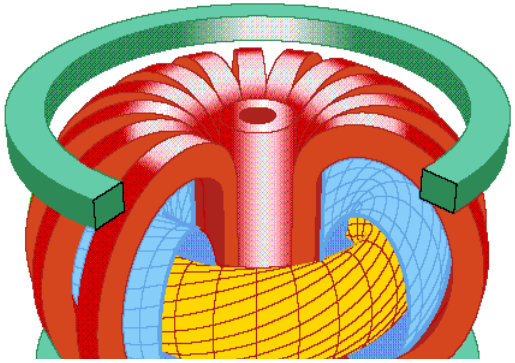
The Tokamak concept

- operationally, it is essentially an electrical transformer
- toroidal magnetic field is produced by external magnetic field coils
- plasma current produces poloidal magnetic field
- result is a set of nested helical surfaces
  ⇒ plasma confinement



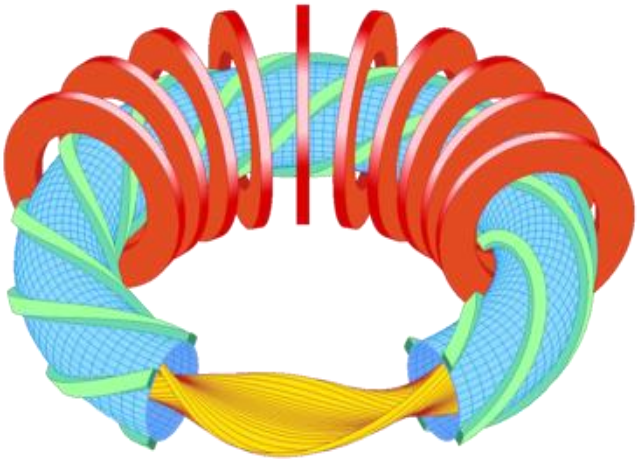
Magnetic Confinement: Tokamak und Stellarator

Tokamak

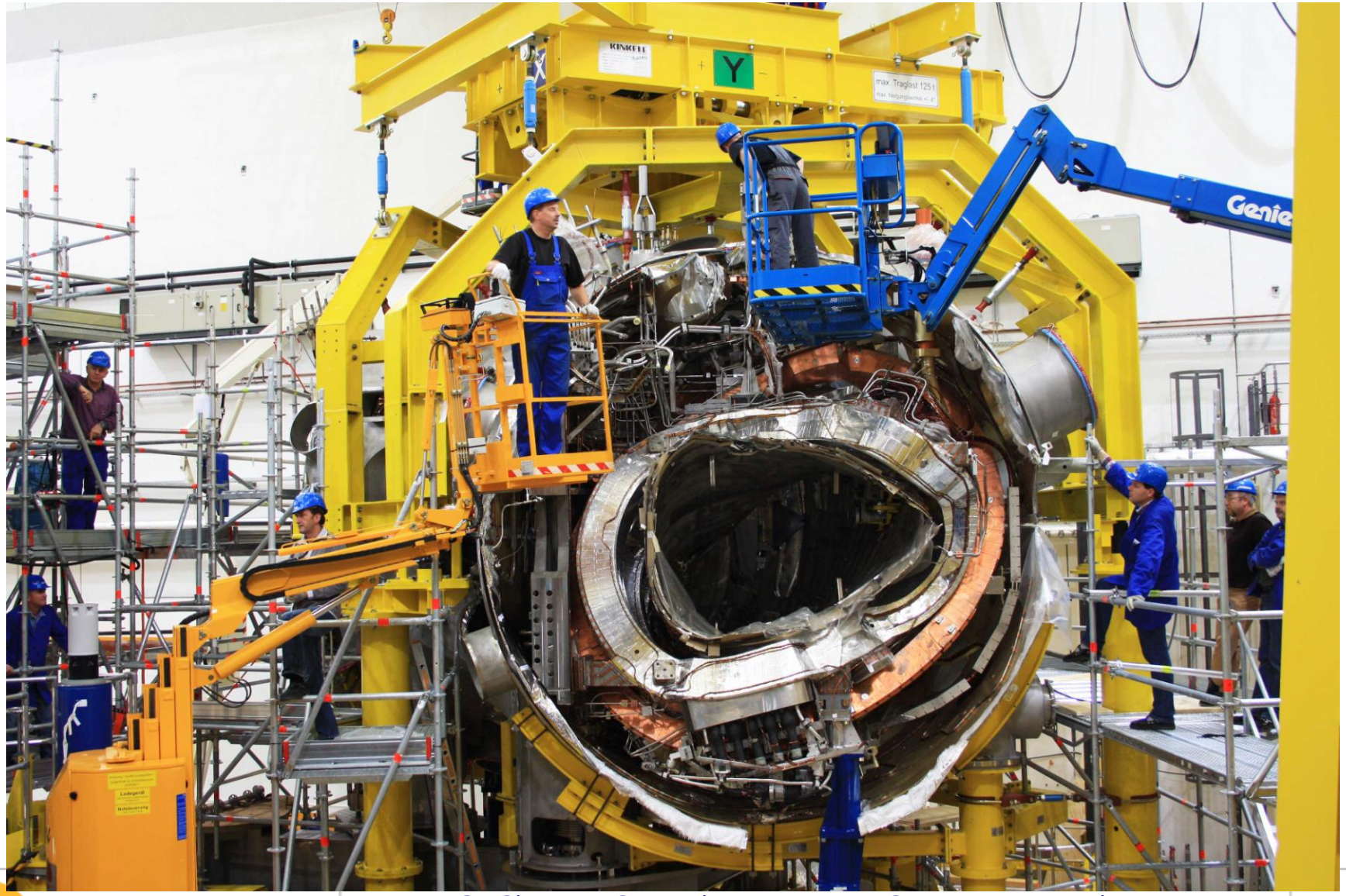


"тороидальная камера в магнитных катушках" (*toroidal'naya kamera v magnitnykh katushkakh*) — toroidal chamber in magnetic coils (Tochamac)).

Stellarator

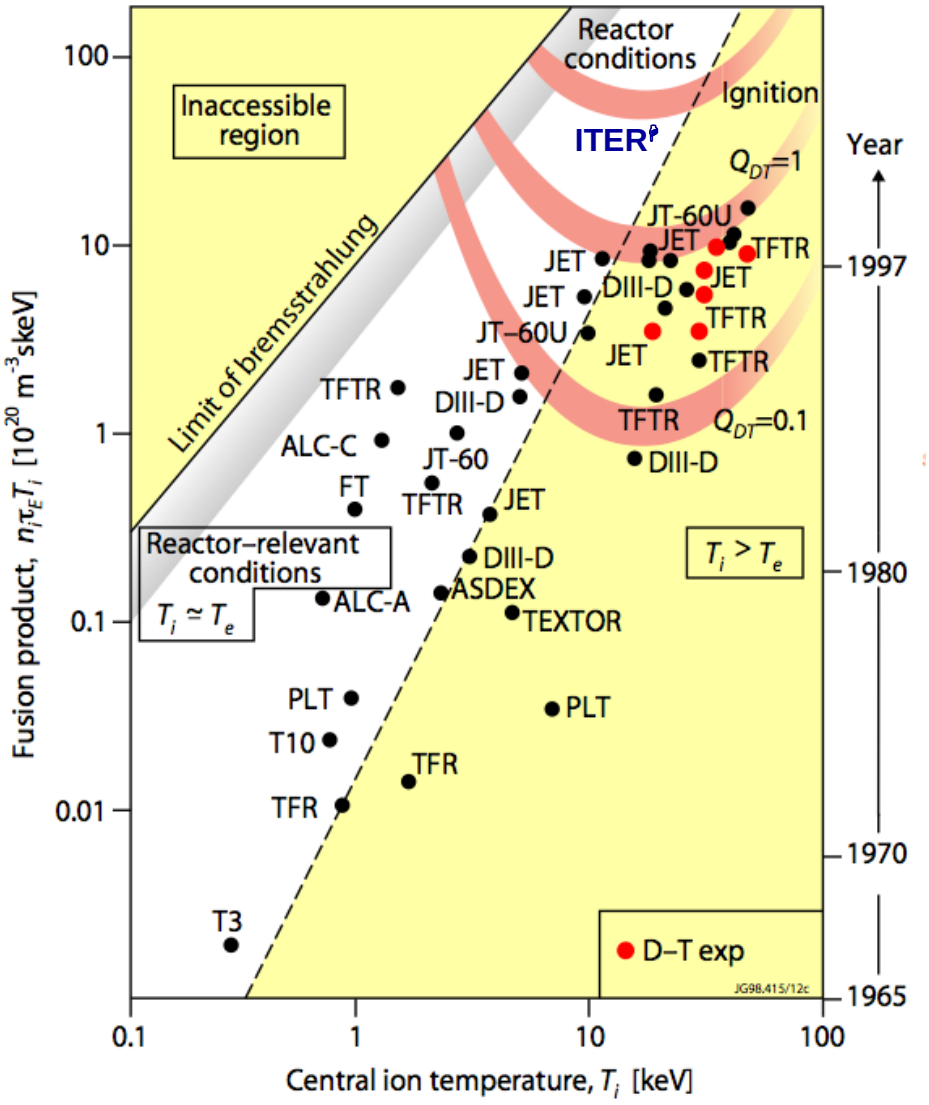


Germany: Wendelstein 7-X: Concept and Construction

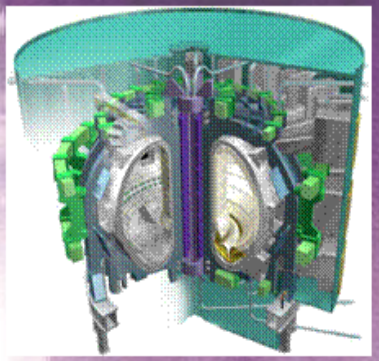


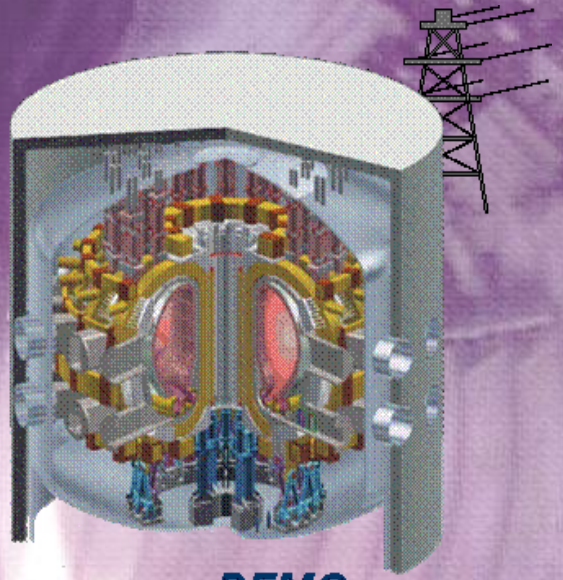
Fusion Triple Product

- Existing experiments have achieved $nT\tau$ values
  ~ 1×10^{21} $m^{-3}skeV$
  ~ $Q_{DT} = 1$
- JET and TFTR have produced DT fusion powers of >10MW for ~1s
- ITER is designed to a scale which should yield $Q_{DT} > 10$ at a fusion power of ~ 500MW for ~400s and up to 3000s



ITER -the way to fusion energy





Tore Supra
25 m^3
~ 0 MW_{th}

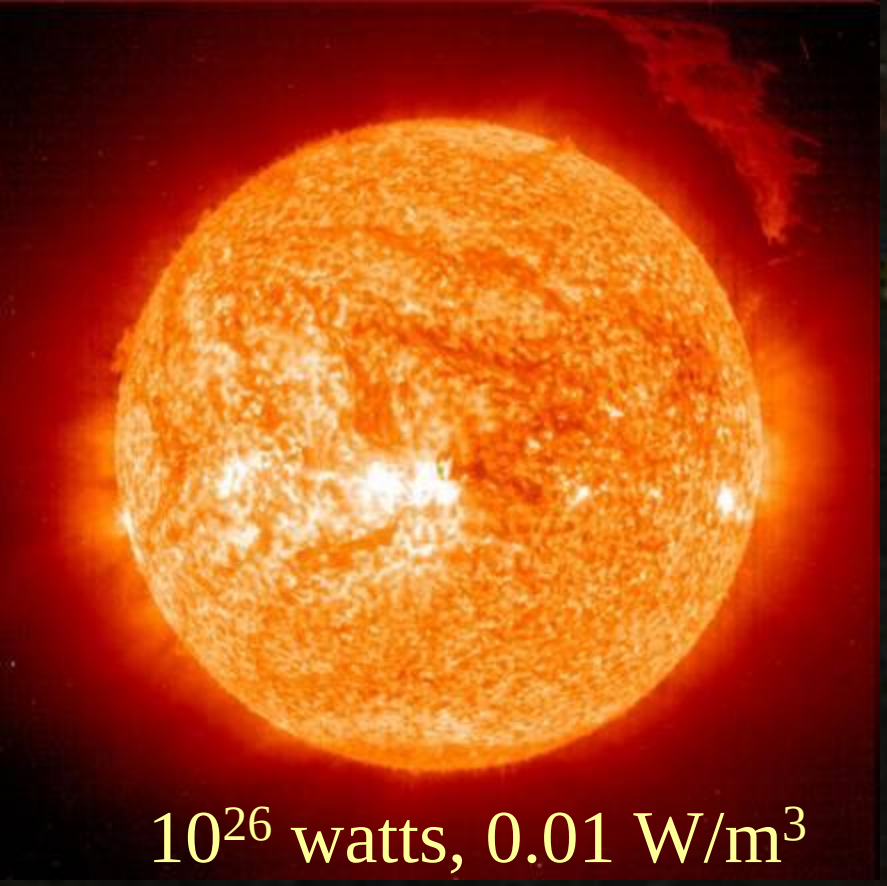
JET
80 m^3
~16 MW_{th}

ITER
800 m^3
~ 500 MW_{th}

DEMO
~ 1000 - 3500 m^3
~ 2000 - 4000 MW_{th}

- Dominant self heating ---------->

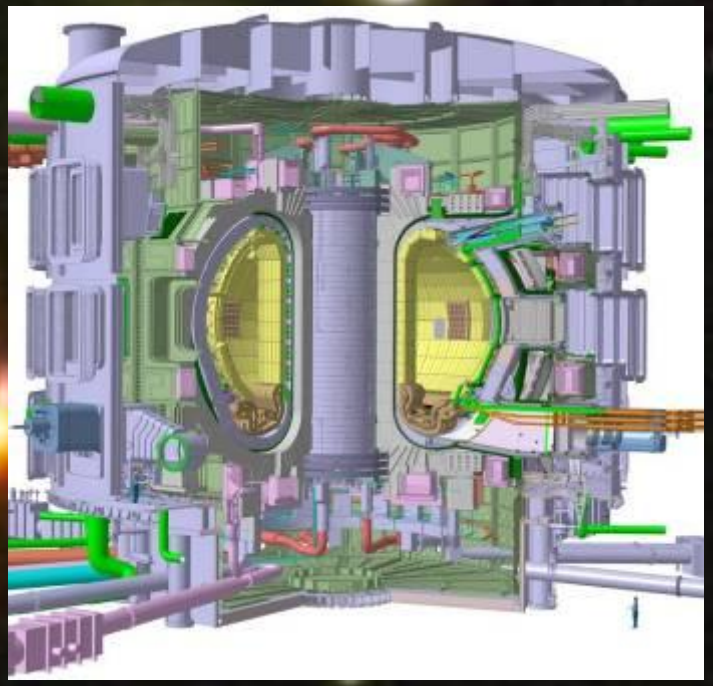
JG99.518/2c



10^{26} watts, 0.01 W/m^3

- The Sun has a radius of 0.7 Million kilometer
- A core temperature of 10 Million deg
- A surface temperature of ~4000 deg

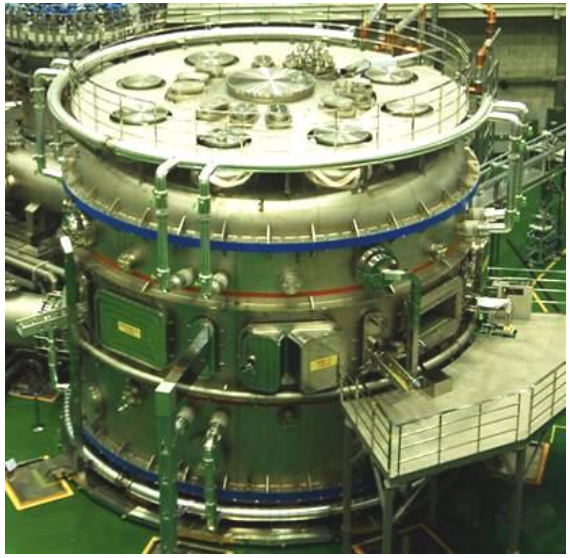
- The Tokamak chamber has a radius of 2 meter
- A core temperature of 100 Million deg
- The wall surface has a temperature of ~1000 deg



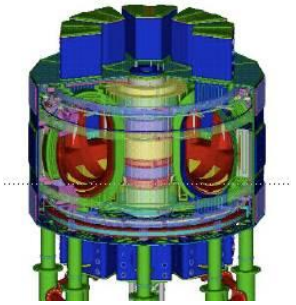
5.10^8 watts, 5 10^5 W/m^3

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

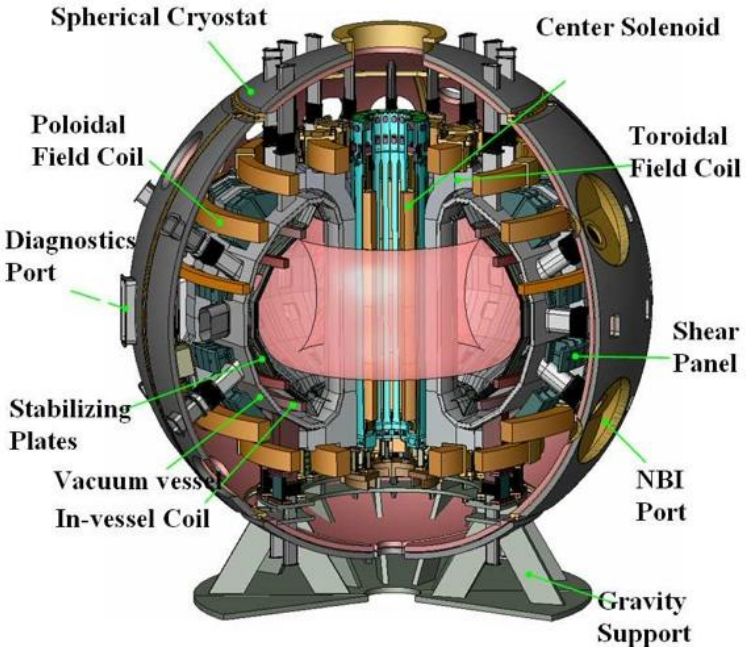
EAST: R = 1.7m, 2MA, 2006



KSTAR: R = 1.8m, 2MA, 2008



SST-1: R =1.1m, 0.22MA, 2008



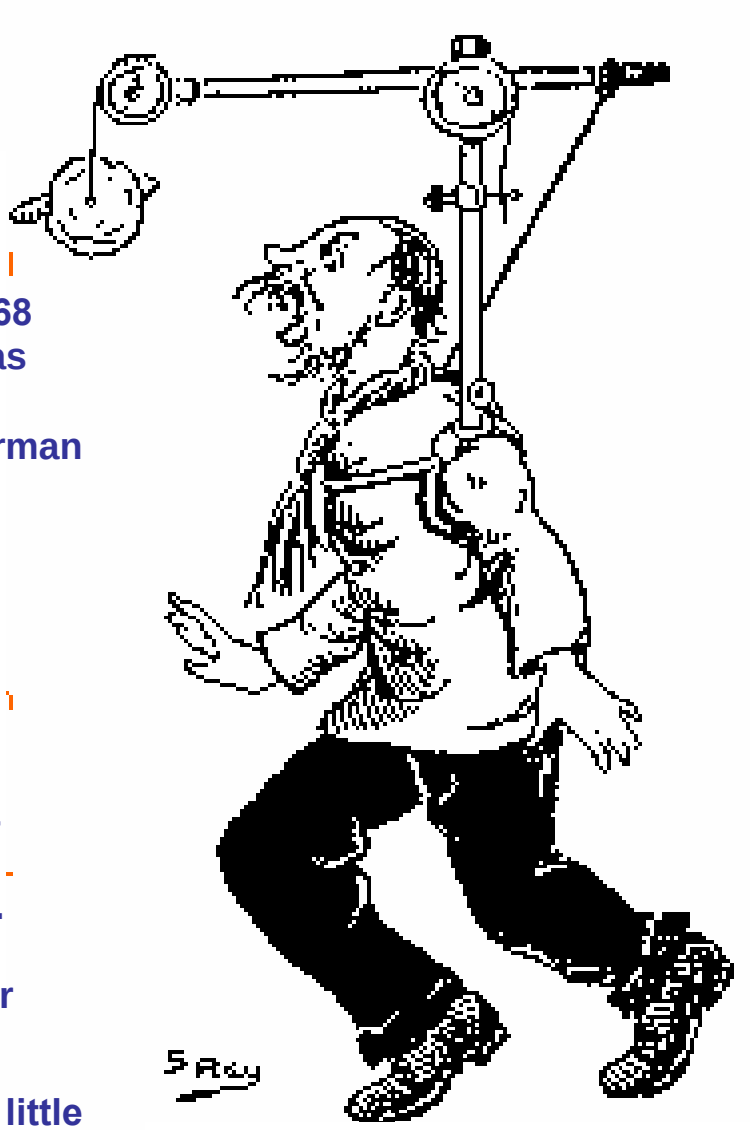
JT-60SA: R = 3m, 5.5 MA, 2014

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=>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…

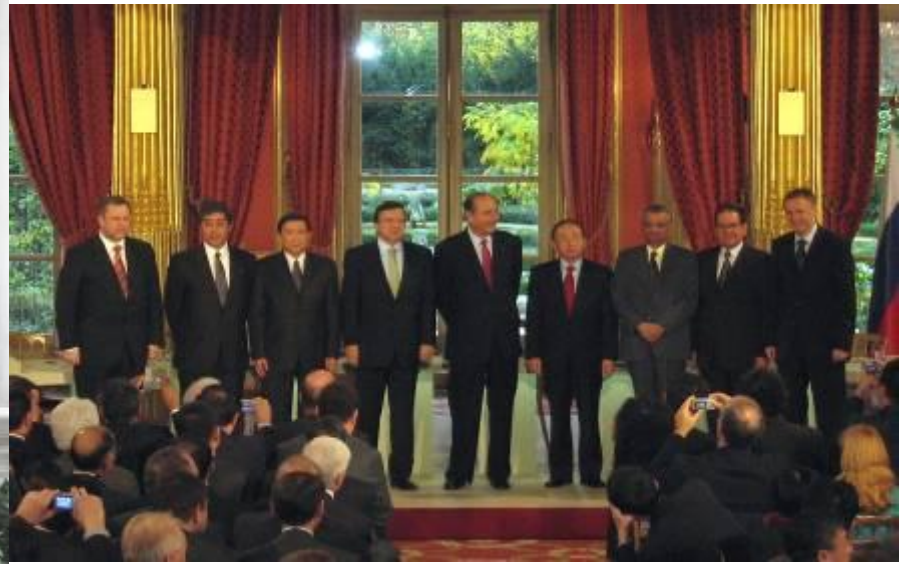


The dangling "Carrot" ….

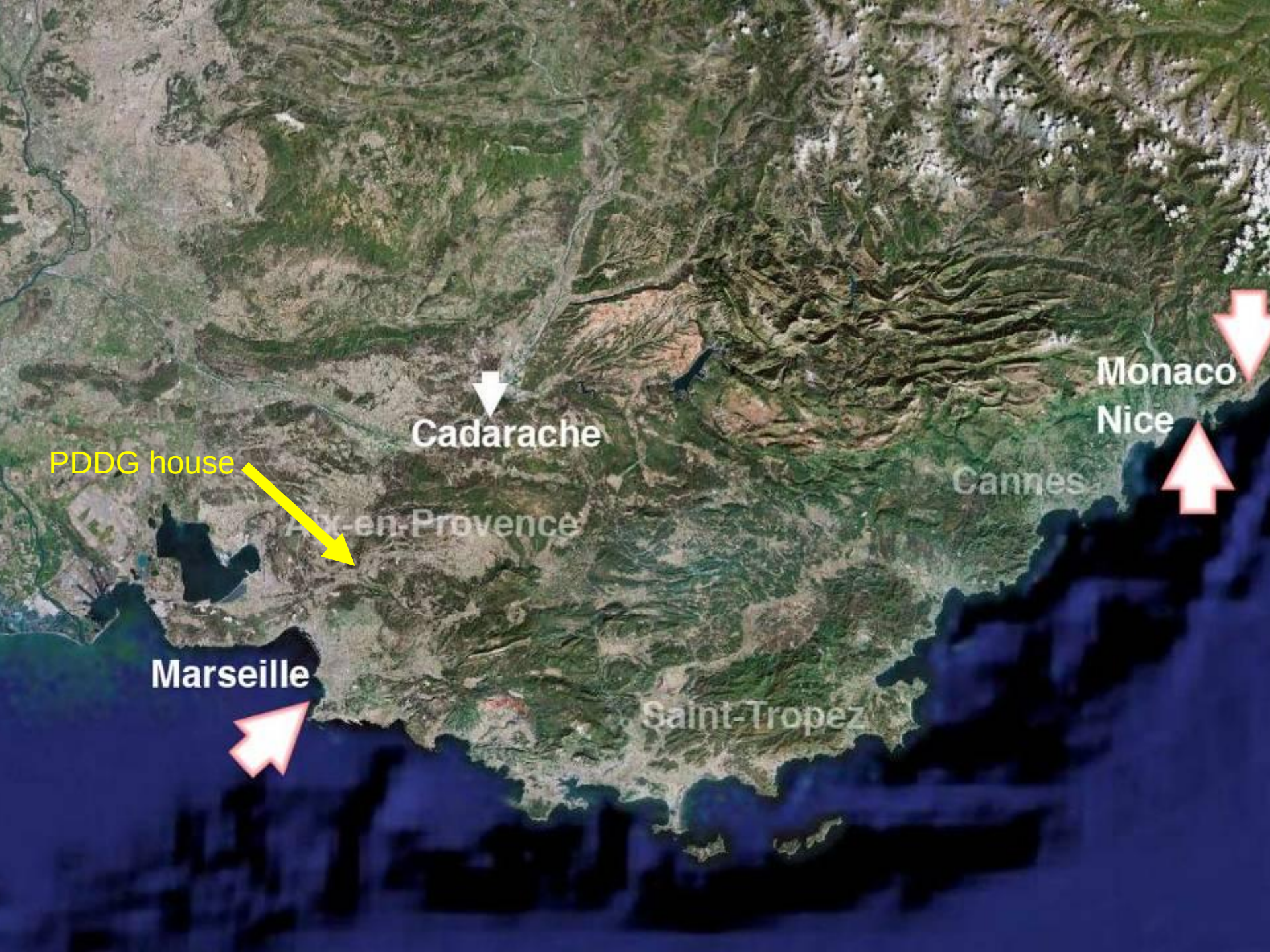
"*For the benefit of mankind*"

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

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



November 21, 2006:
China, Europe, India, Japan, Korea, Russian Federation and the United States of America sign the ITER Agreement


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

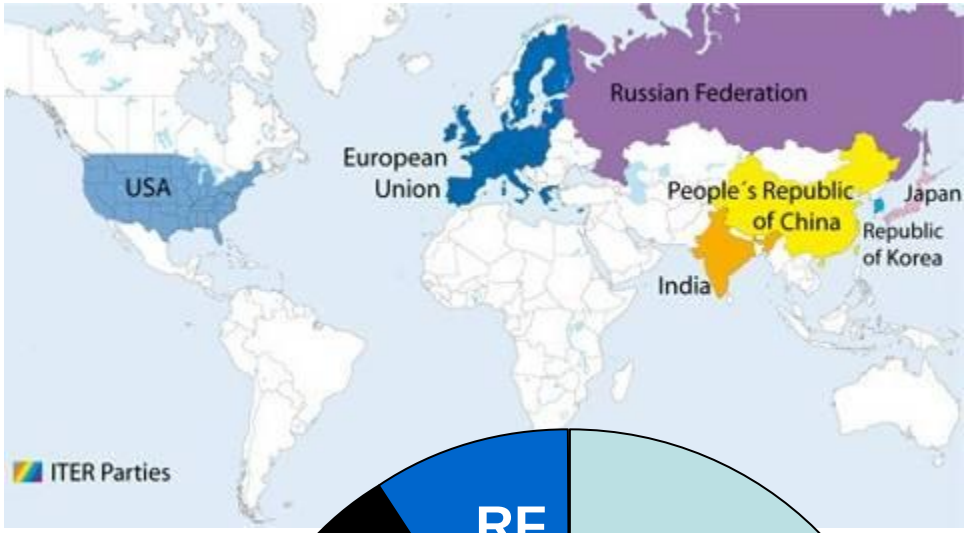
Staffing Status

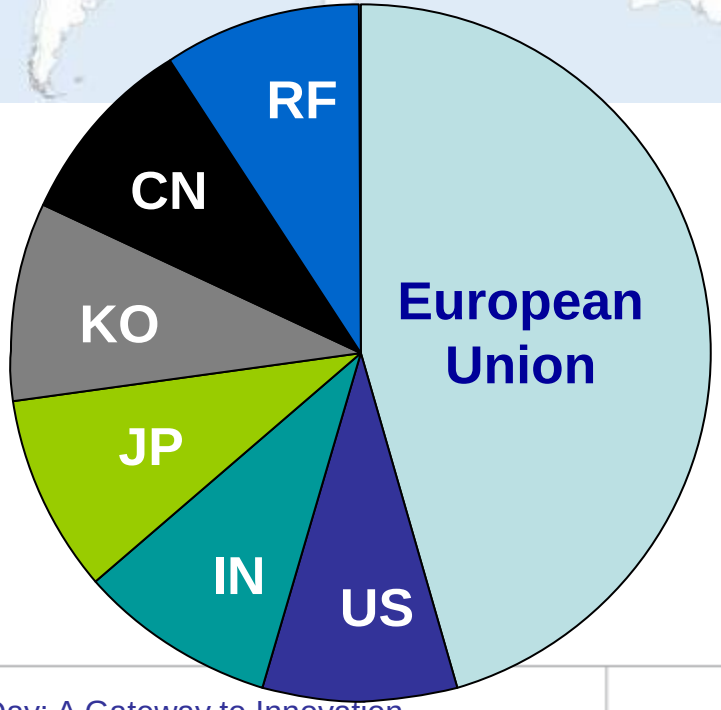
- By 31 December 2009, the ITER Organization had a total of 430 staff members, comprising 291 professional and 139 technical support staff members. In addition, as of end of 2009 there were around 330 external contractors.

	Professional staff	Support staff	Total
CN	16	1	17
EU	175	106	281
IN	14	14	28
JA	22	6	28
KO	20	4	24
RU	21	2	23
US	23	6	29
Total	291	139	430

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 with a Q of 10**
- **10 years construction, 20 years operation**
- **Cost: ~5.6 billion Euros approved for construction, and ~5.5 billion for operation and decommissioning**
- **EU 5/11, other six parties 1/11 each. Overall reserve of 10% of total.**

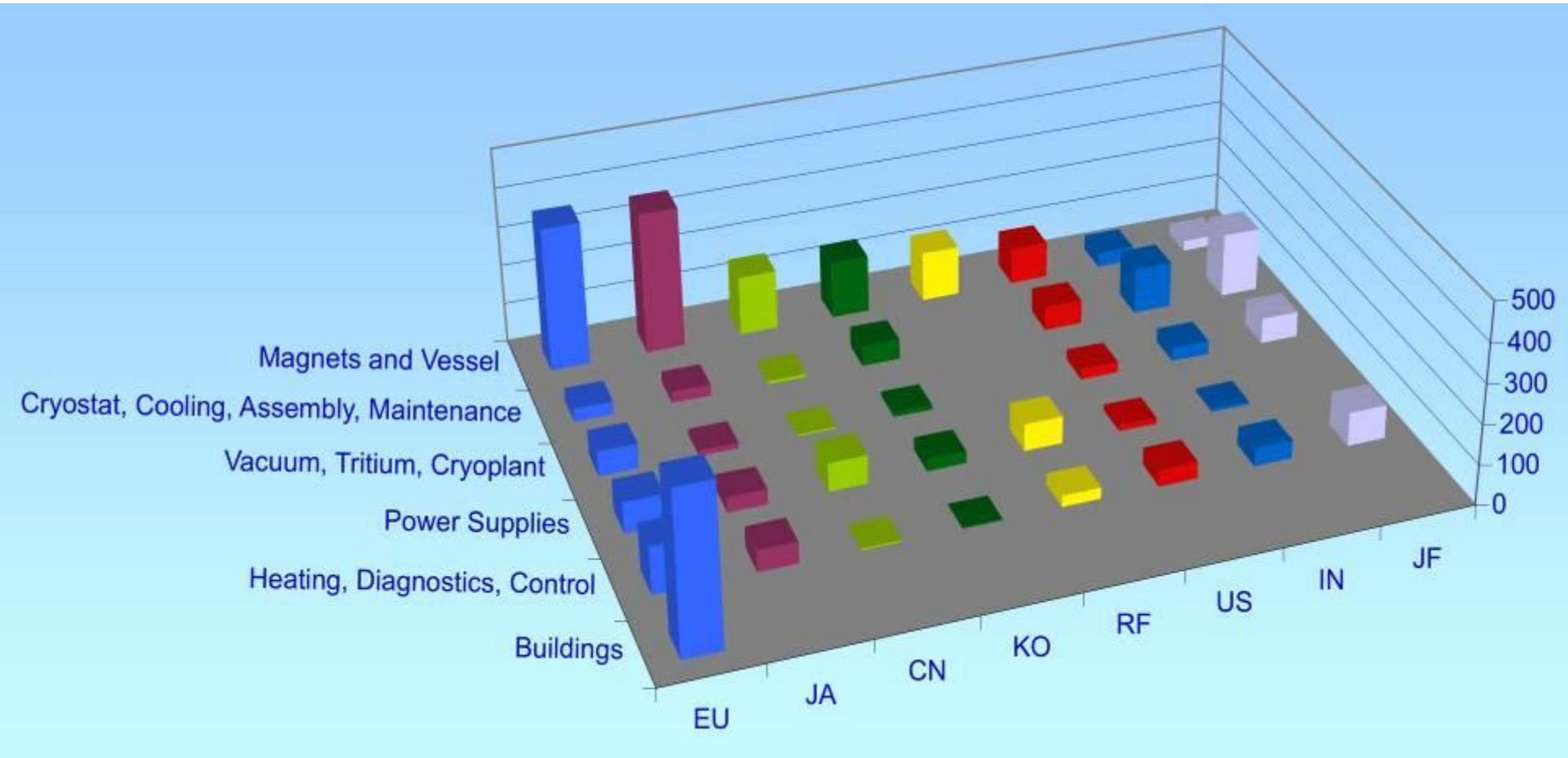




- The ITER Organization and the ITER Domestic Agencies

Procurement Sharing

- A unique feature of ITER is that almost all of the machine will be constructed through *in kind* procurement from the Members with essentially every member involved in every component.



Integration between IO and DAs
- Basic Roles and Responsibilities -

ITER Organization	Seven Members (Domestic Agencies, DA)
– Planning / Design* – Integration / QA / Safety / Licensing / Schedule – Installation – Testing + Commissioning – Operation	– Detailing / Designing* – Procuring / Manufacturing – Delivering – Supporting installation – Conformance

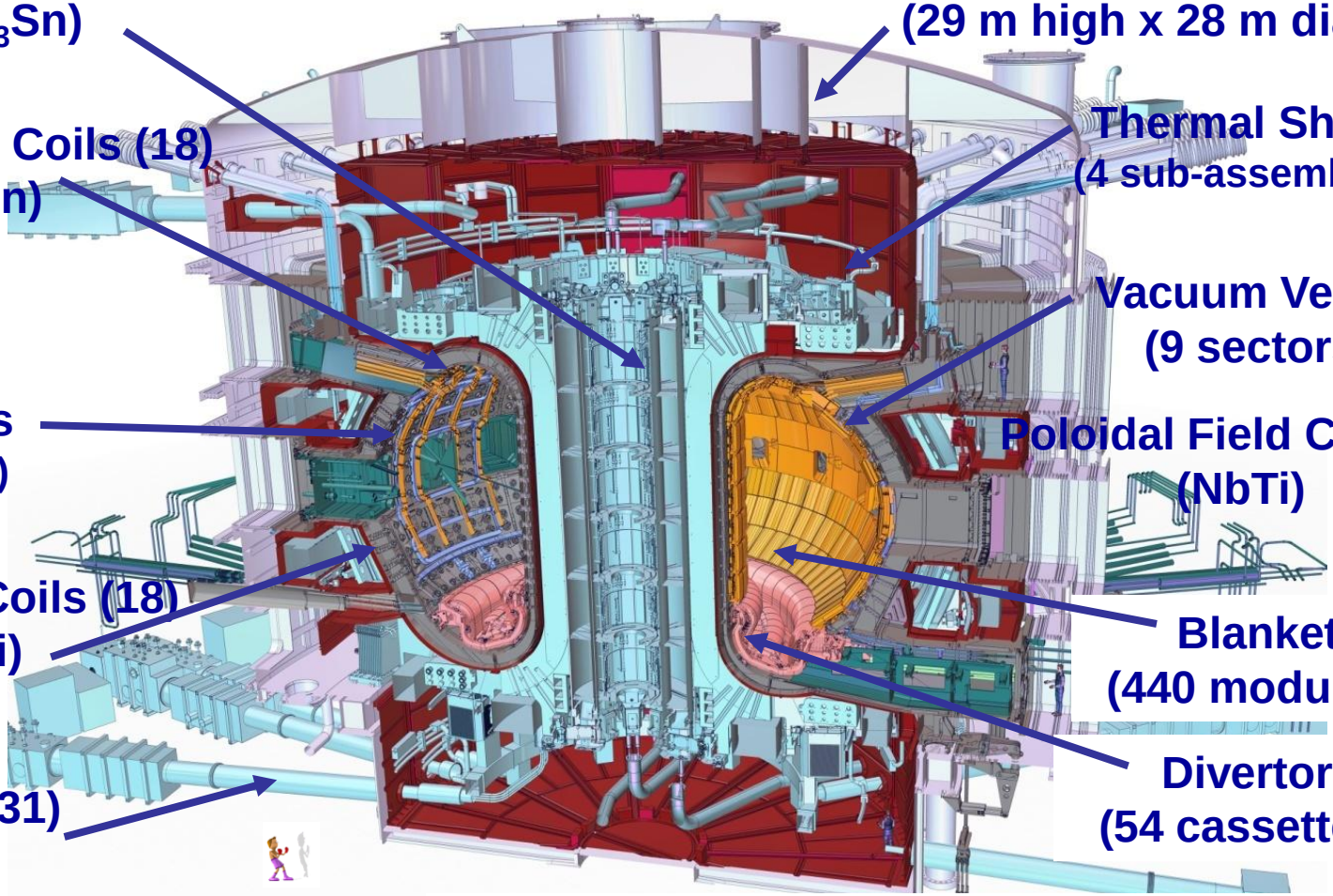
***** Depending on type of specification
- Functional: Functional requirements by IO and design by DAs
- Detail design: Conceptual design by IO and detailed design by DAs
- Build-to-print: Detailed design by IO and fabrication/shop design by DAs

Project Status

- In parallel to a design review that finished in 2007, the scope of ITER was fixed in June 2008. Actual cost details and an executable schedule is established.
- The “First Plasma” initiation is planned for Nov 2019. The full performance DT Operation for 2027
- The council will approve July 27 2010 the baseline together with the cost increase of ITER in its next meeting.
- As of today, there are a total of 45 signed PAs, amounting to 1732.5 kIUA (approximately EUR 2688.2 in 2010 value), about 60% of the total procurement value.
- Another 15 PAs are scheduled to be signed by the end of 2010 for a total of 429.3 kIUA (an estimated EUR 666.4 million in 2010 value) which will bring this to > 72%.

Status of ITER's technical progress (highlights)

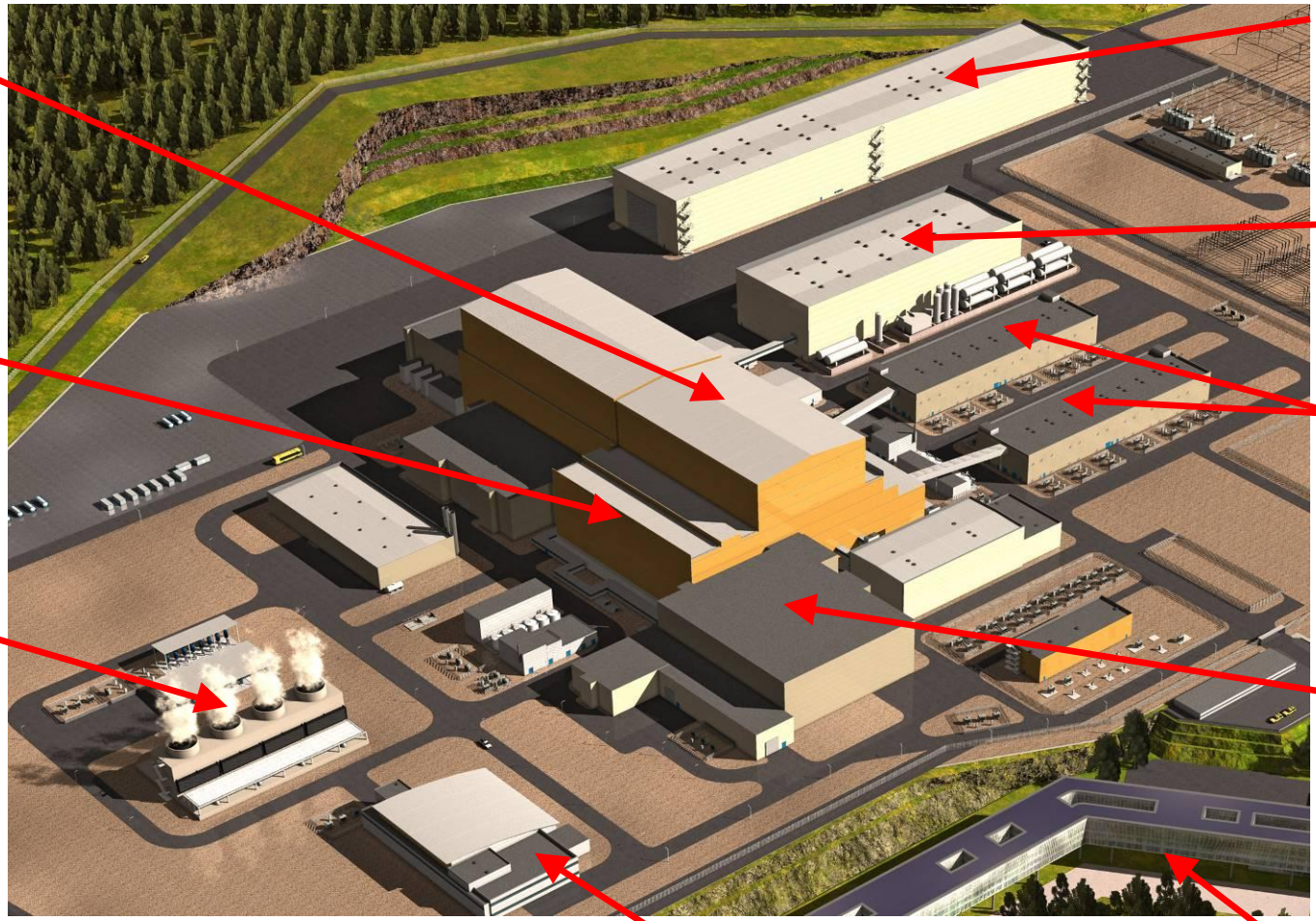
Fusion gain Q = 10, Fusion Power: ~500MW, Ohmic burn 300 to 500 sec
Goal Q=5 for 3000 sec



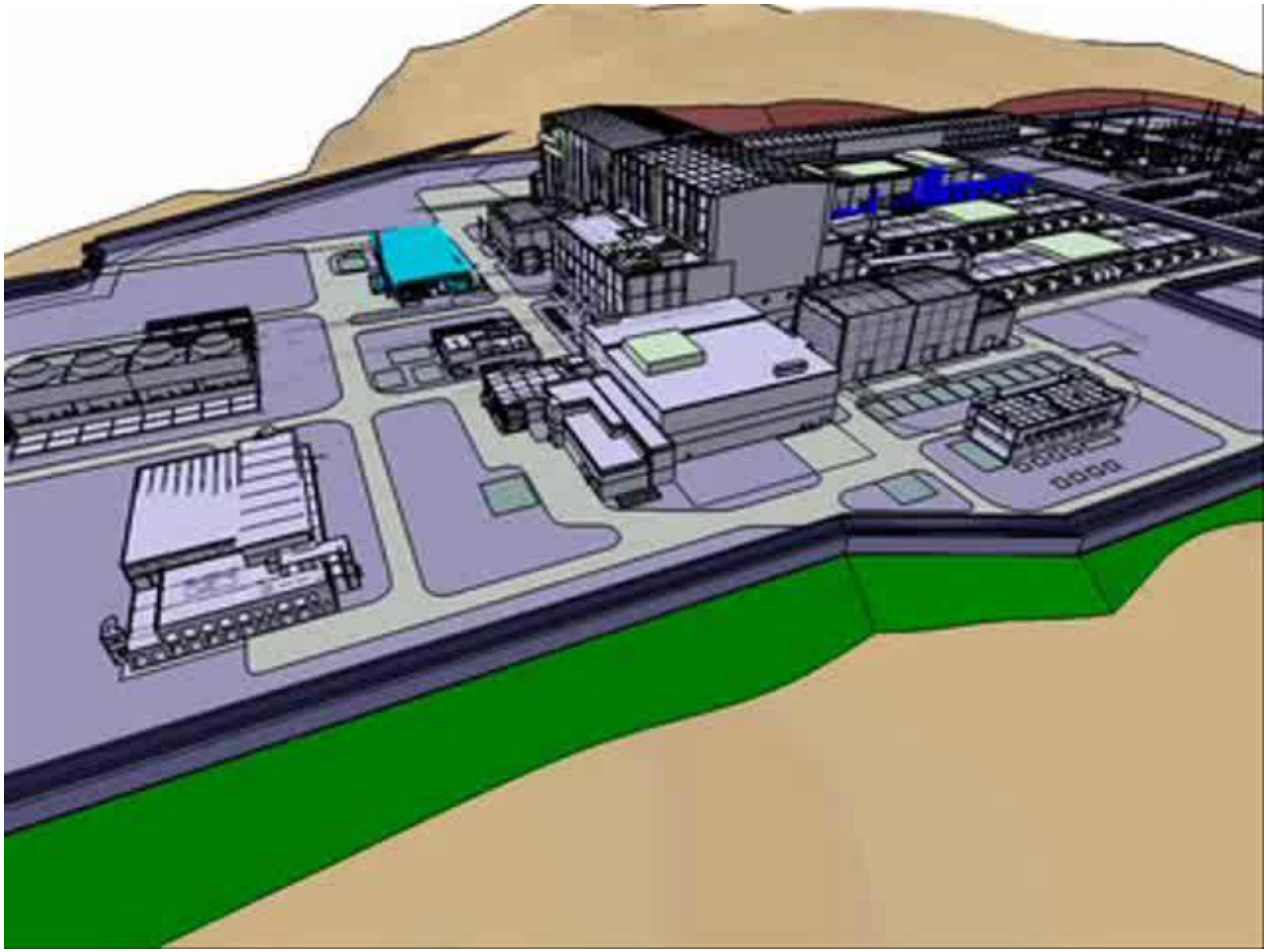
Machine mass: 23350 t (cryostat + VV + magnets)
- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t

Main Buildings on the ITER Site

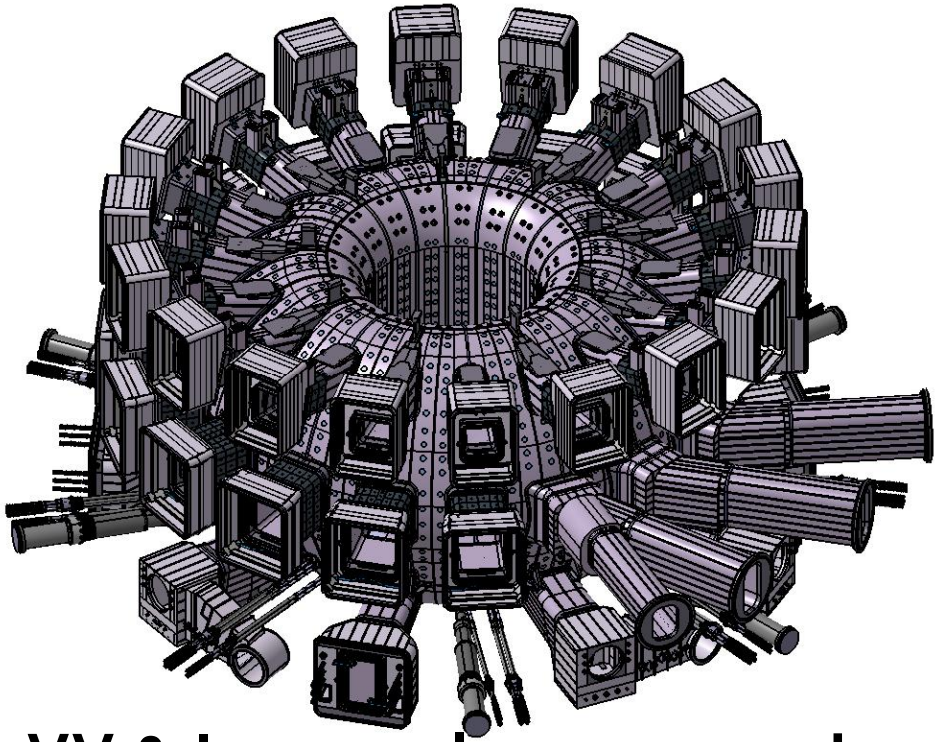
A facility licensed under the French Nuclear Regulatory Authority (ASN)



- Will cover an area of about 60 ha
- Large buildings up to 250m long
- Large number of systems



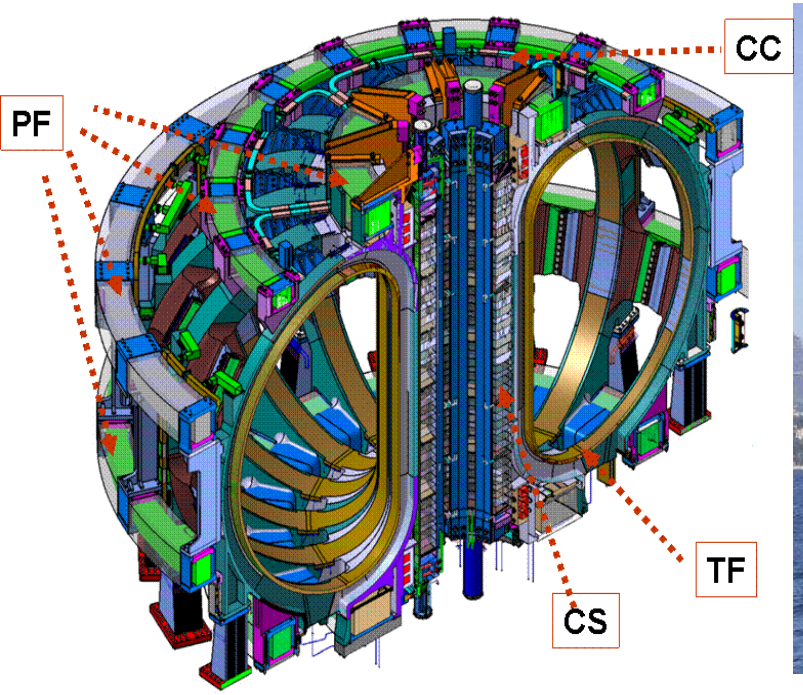
Vacuum Vessel Mass Comparison



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)

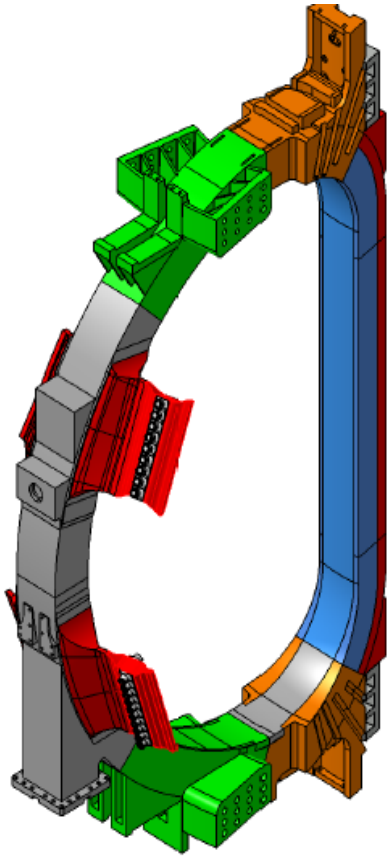
Magnet Energy Comparison



Superconducting Magnet Energy:
~51 GJ

Charles de Gaulle Energy:
~38000 t at ~150 km/hr

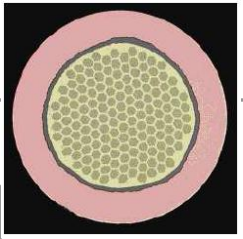
TF Coil – Mass Comparison



Mass of (1) TF Coil:
~360 t
16 m Tall x 9 m Wide

Boeing 747-300
(Maximum Takeoff Weight)
~377 t

Conductor



Strand

1st Stage

3rd Stage

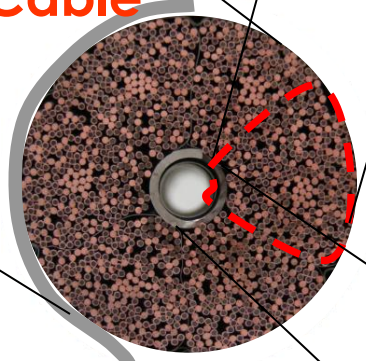
Sub-Wrap

Cu Wire

2nd Stage

Cable

4 th Stage

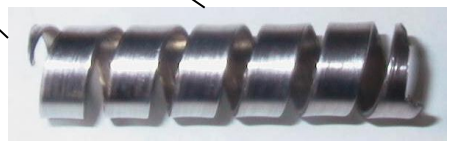


Cu Core Cable

Cu Sub-Cable

Jacket Assy

Wrap



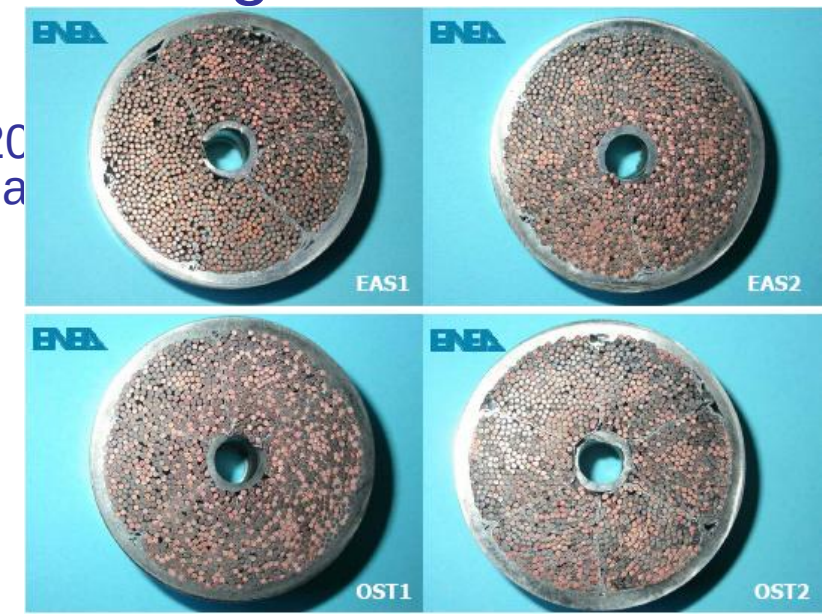
Central Spiral

Jacket

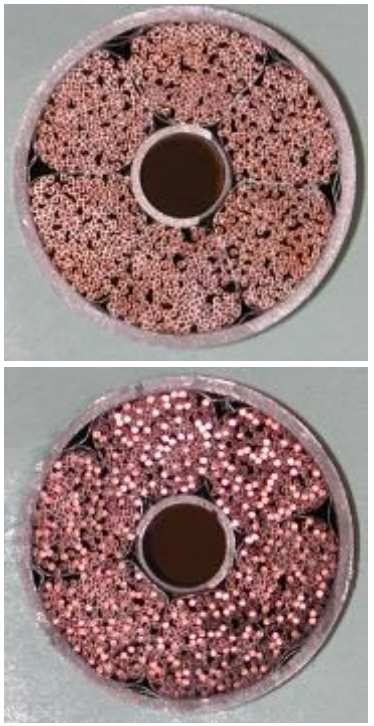
The Fix: Packing of the conductor wire…

Magnet Conductor

- cables tested in 20 showed substantia degradation



- Ongoing field-cycling stress tests showing very promising results



Cables from all 6 parties that make them are qualified now!

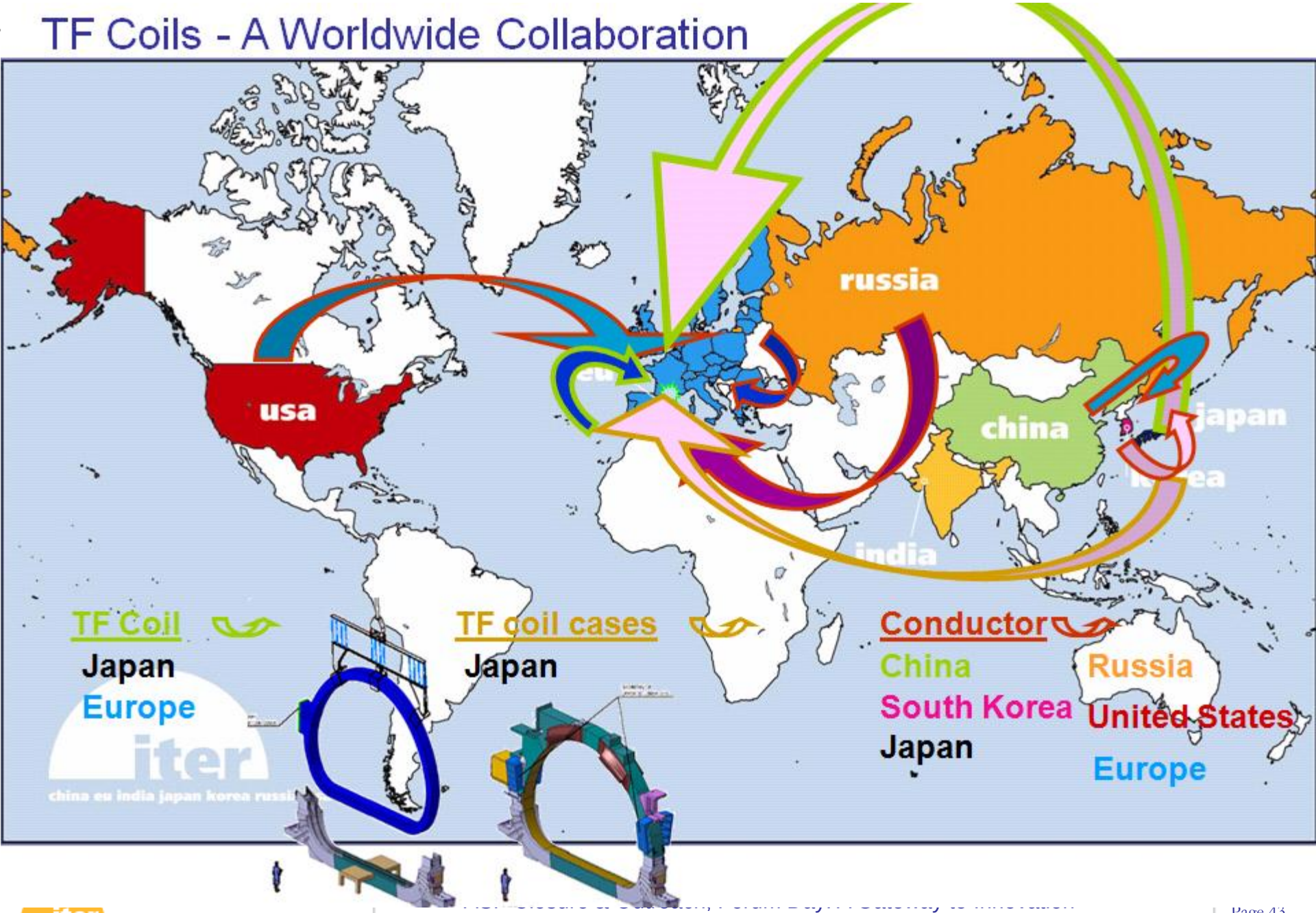
TF and CS Jacketing in JA

TF and PF Jacketing in CN

TF & PF Jacketing Lines at ASIPP (March−June 09)

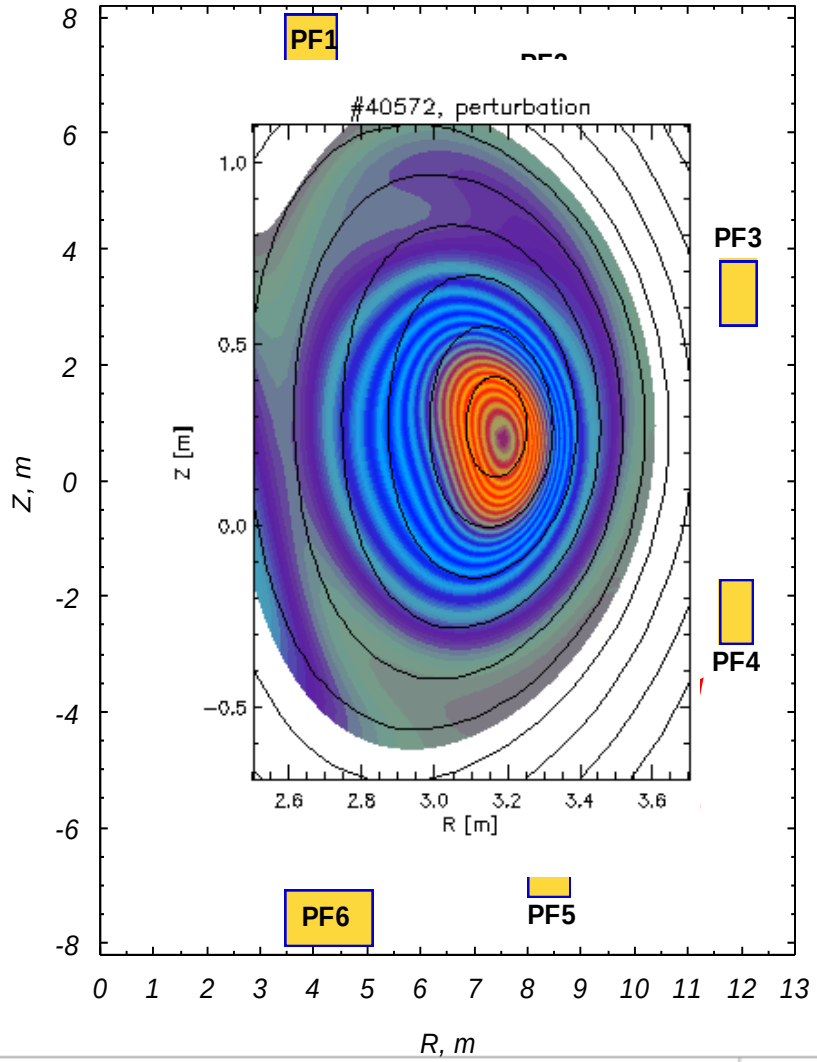
TF & PF Jacketing Lines at ASIPP (March−June 09)

TF Coils - A Worldwide Collaboration



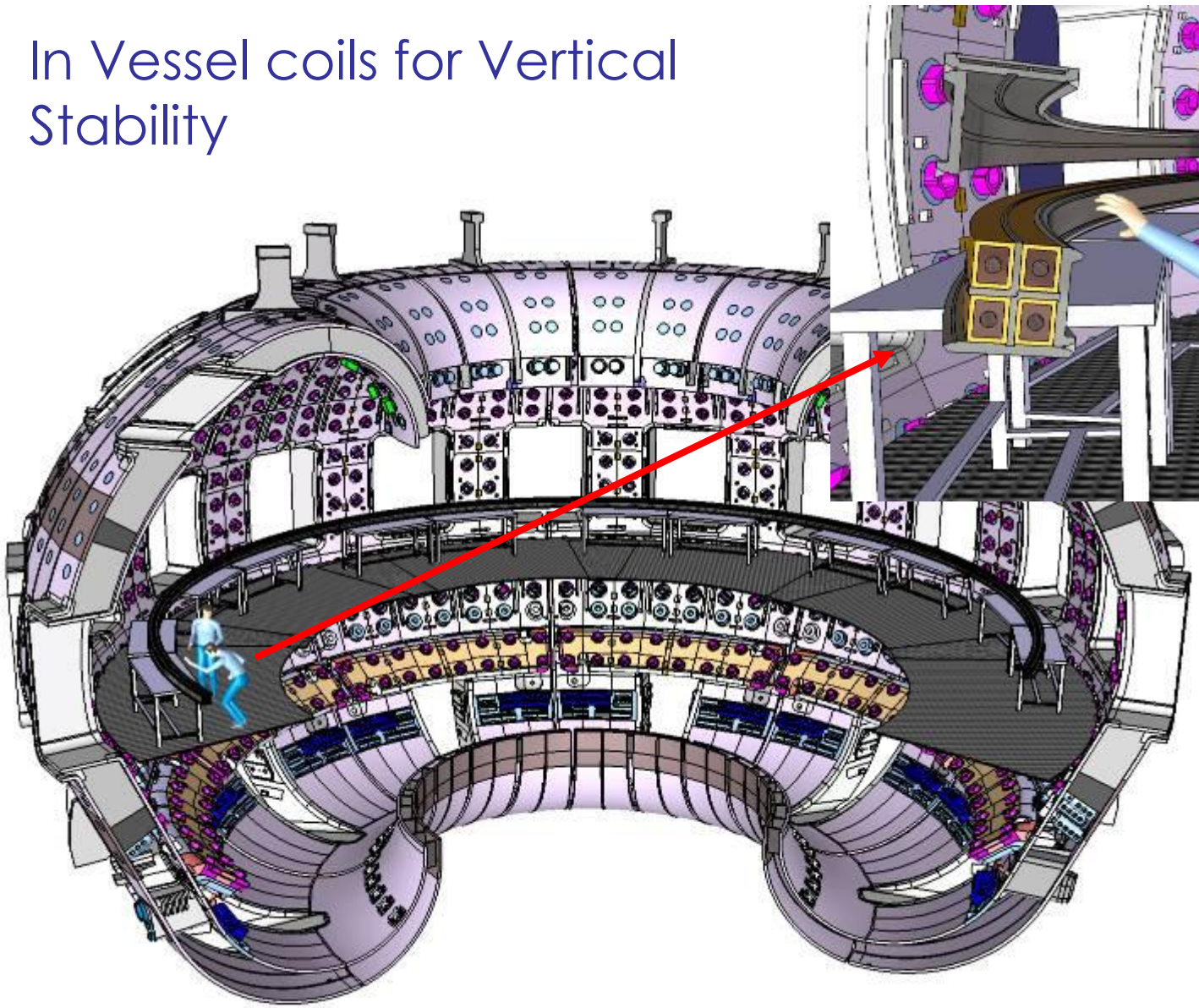
R&D for Projects: Poloidal Field Control in ITER

- Control of the Plasma operation through magnetic fields
- 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)



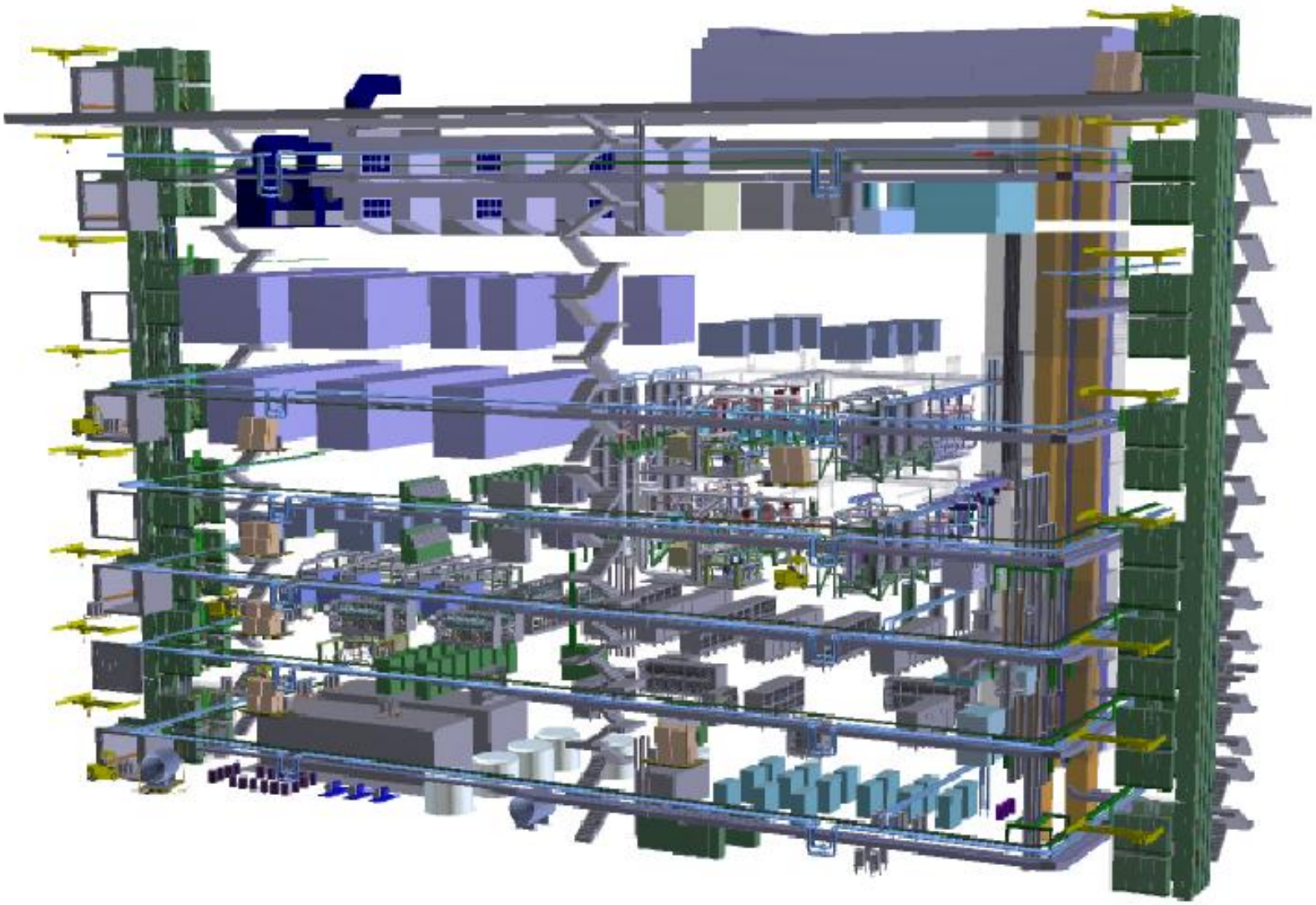
Internal Feedback Coil

In Vessel coils for Vertical Stability

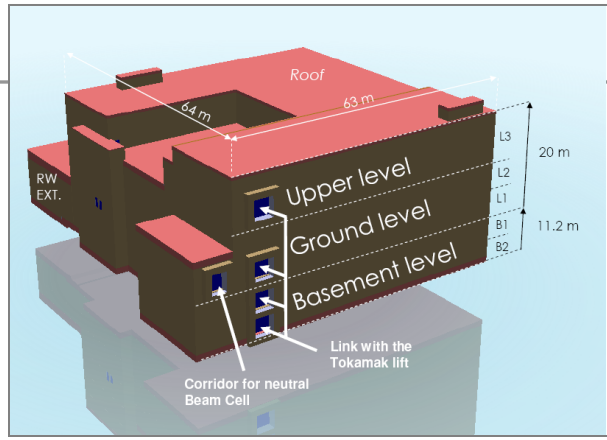


Ongoing R&D for the project

Tritium Plant Building Systems Layout



Hot Cell design



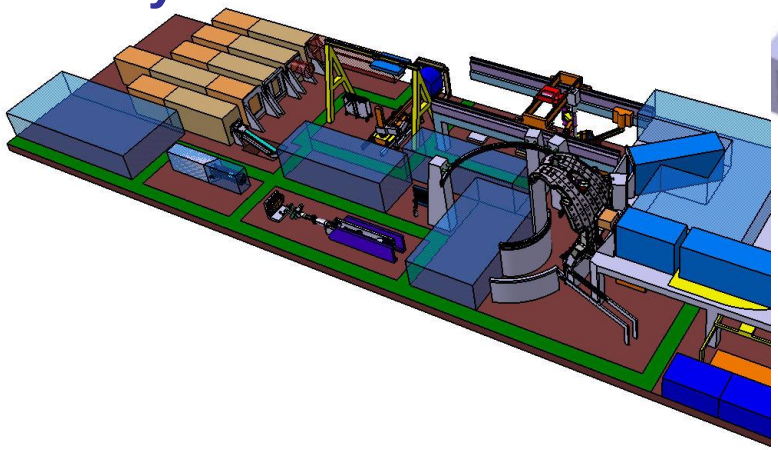
The HC RH system will have the following equipment:

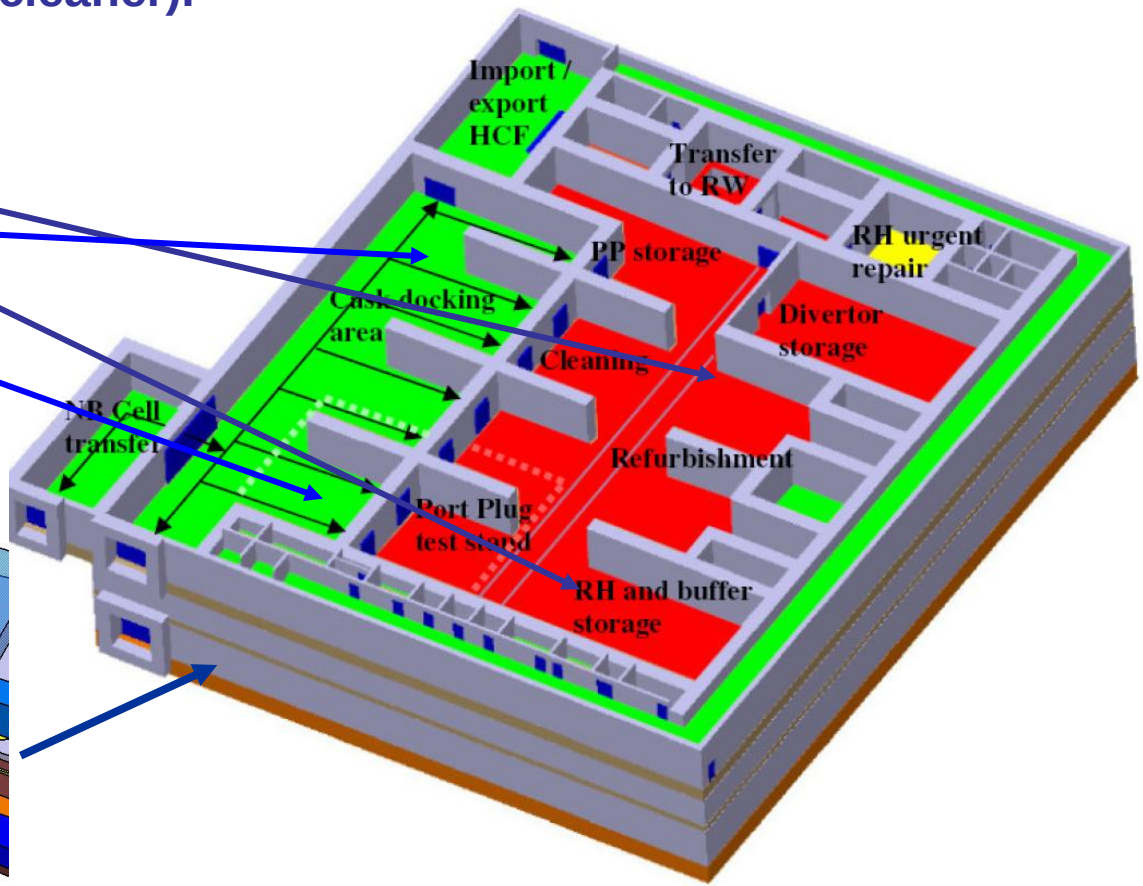
- Boom-style RH transporter(s)
- Jib cranes transporters
- Lifting jigs
- Dexterous telemanipulators) end effectors
- Direct viewing telemanipulators
- Inspection equipment (including weld NDT, visual inspection, metrology)
- Cleaning equipment (Vacuum cleaner).

refurbishment & test

Cask Docking

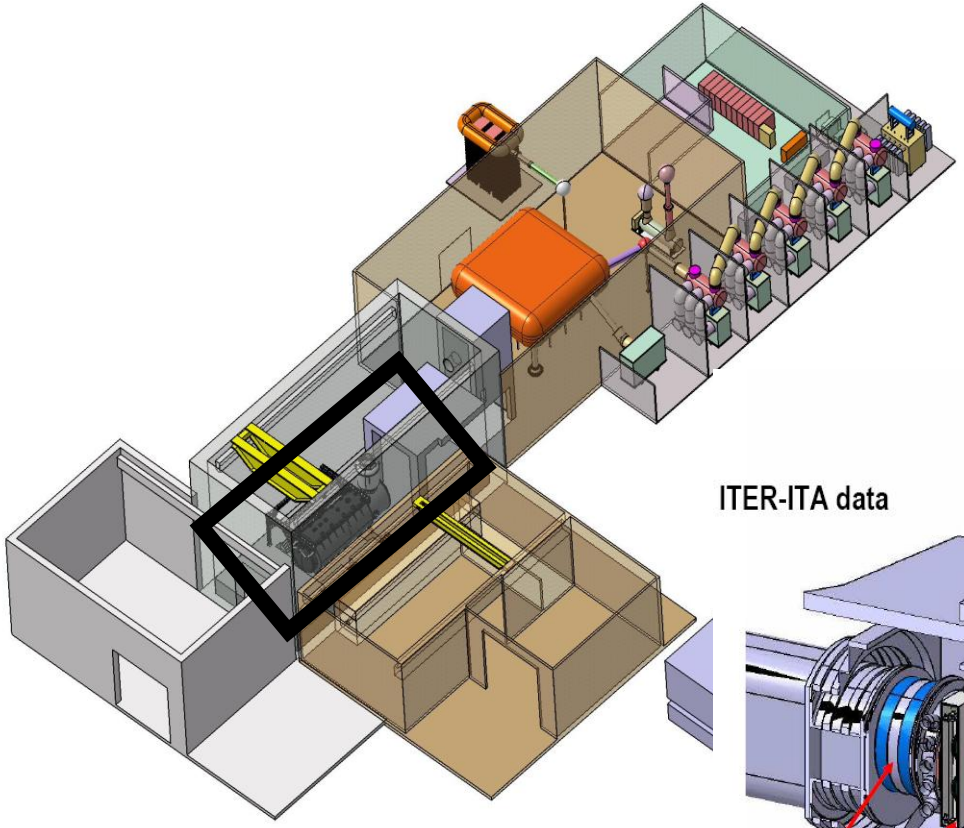
Hot- RH Test facility



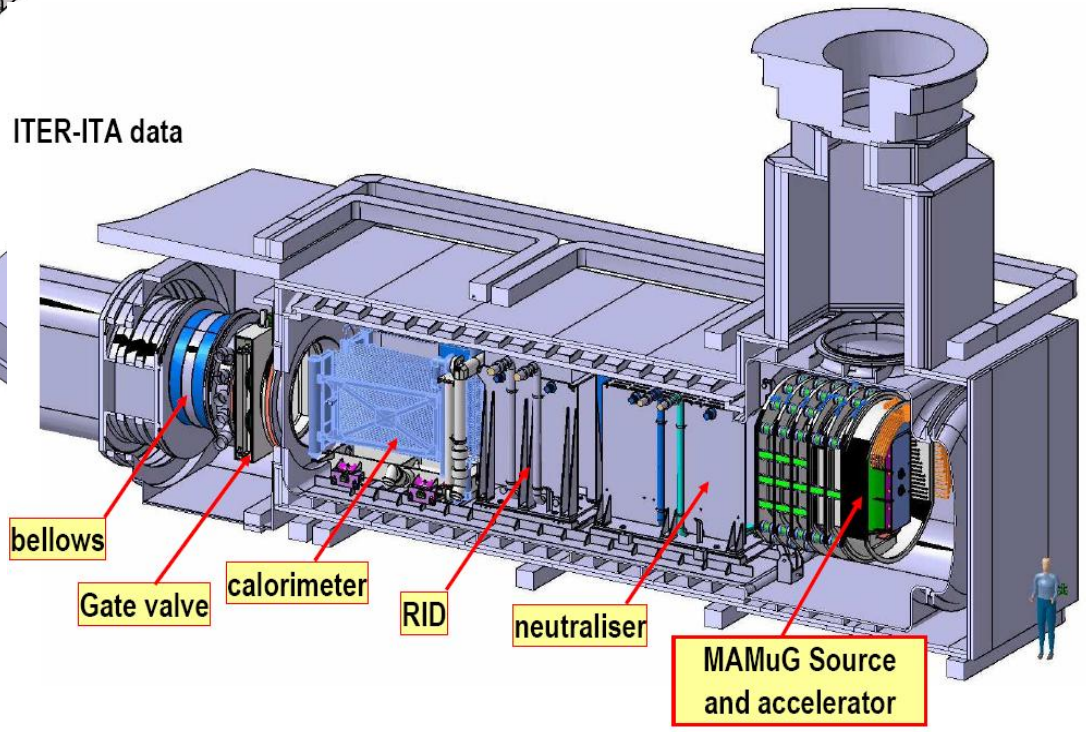


Lay Out Of The Neutral Beam Test Facility in Padua

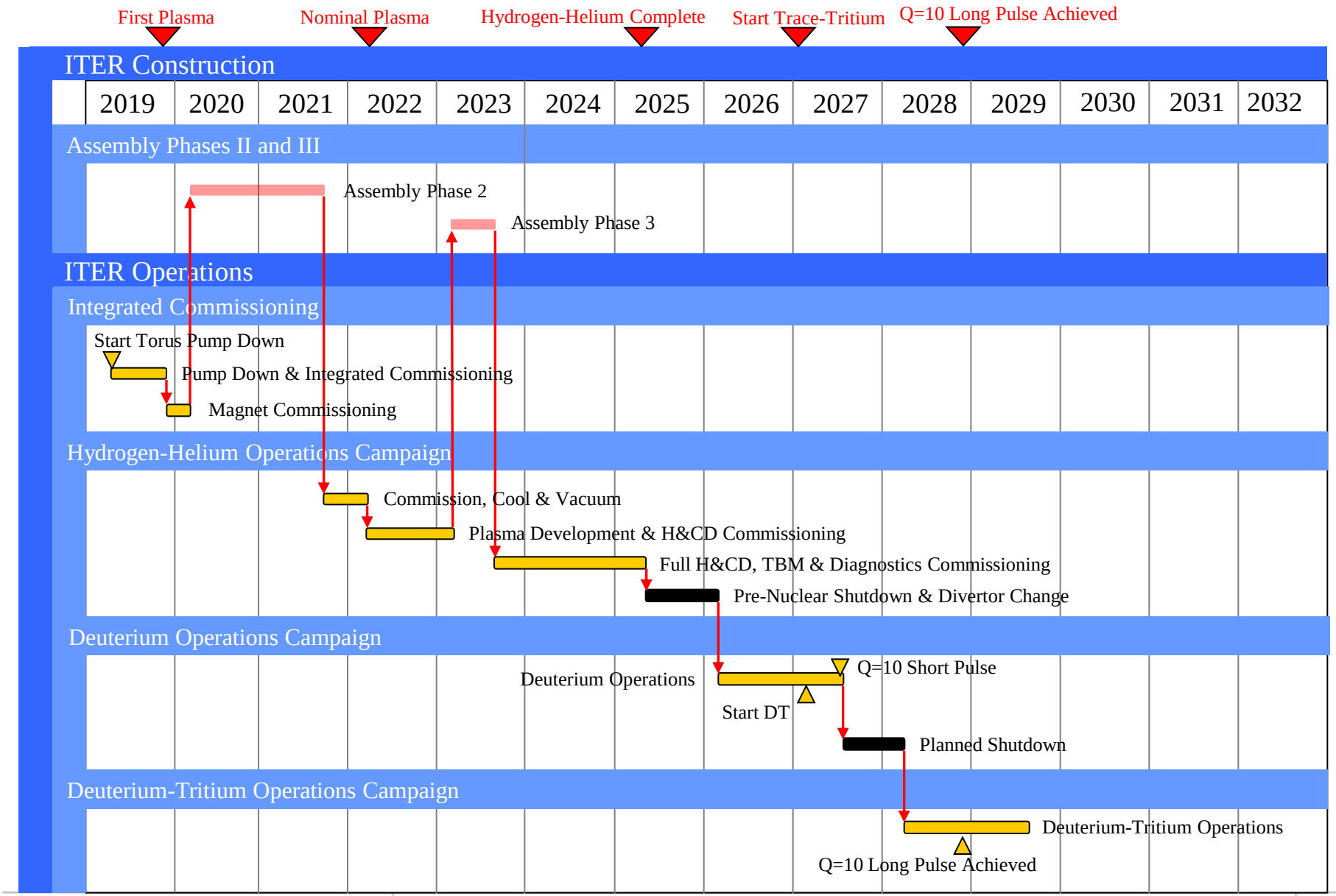
ITER NB Heating System
1 MV DC
~40 A of H^- current
20 MW delivered to Plasma
Up to 3 systems on ITER



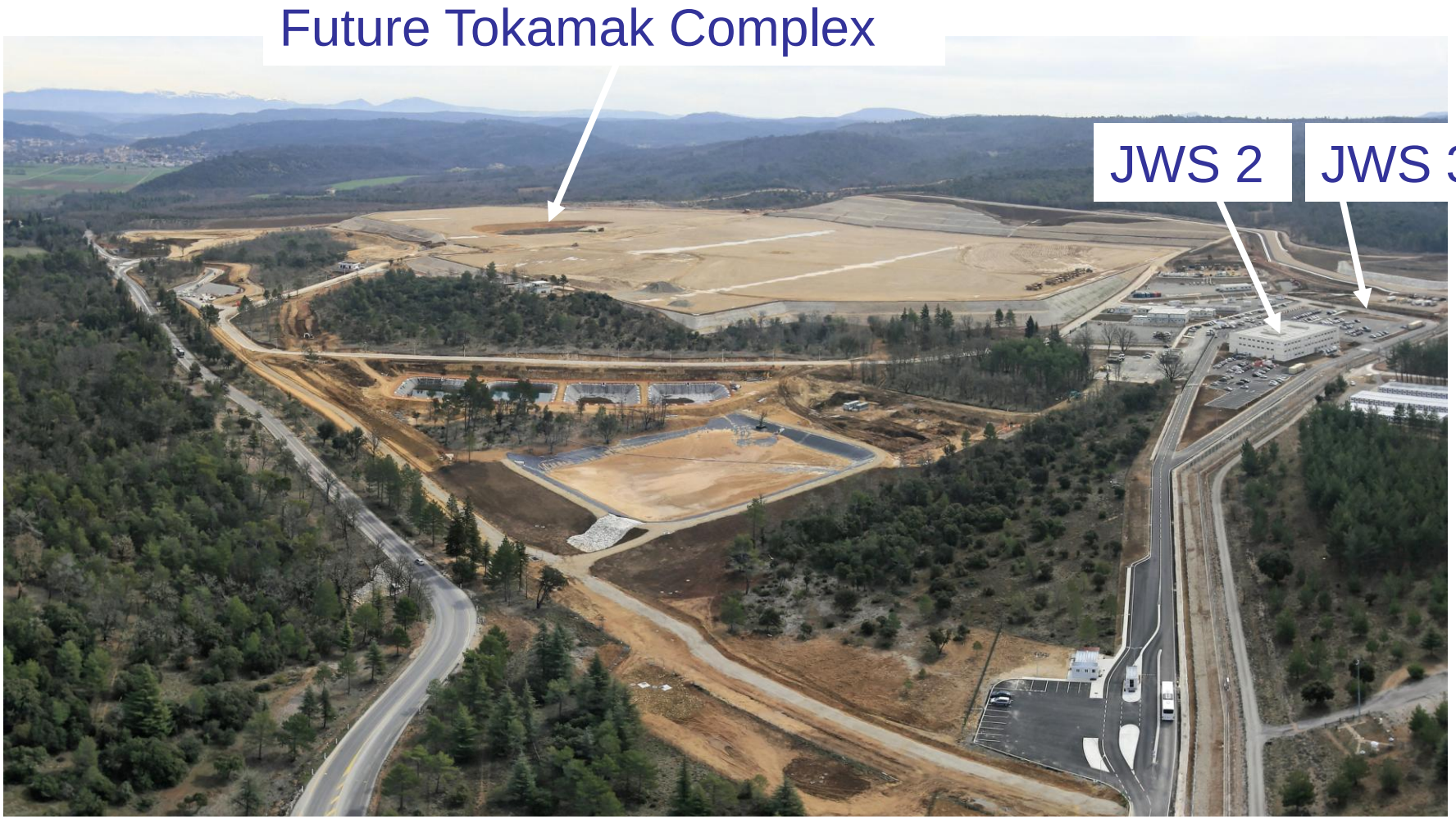
Neutral Beam Test Facility



Overview of Operation up to DT

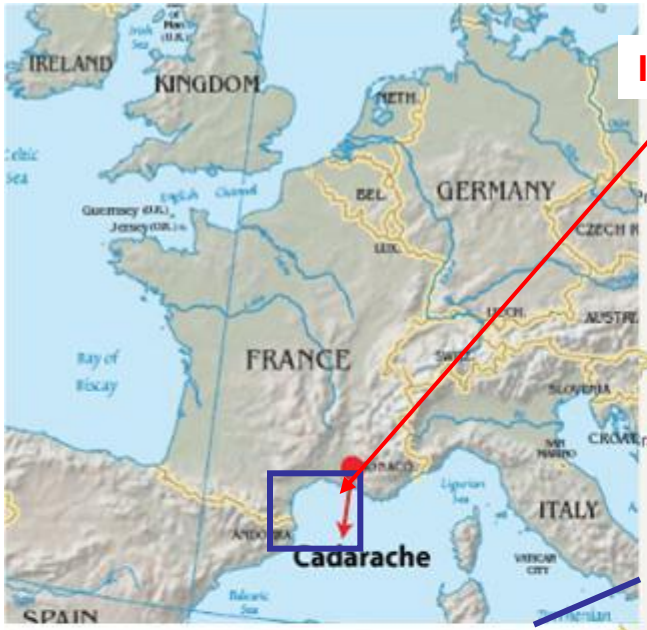


Present ITER Construction Site



The creation and improvement of 106 kilometres of access roads from Fos harbour to Cadarache will be finished by February 2010.

Itinerary of ITER Components



ITER Site

= Itinerary of ITER Components

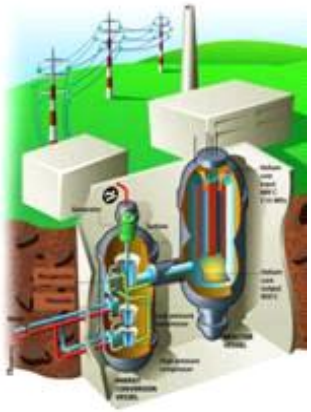
The Roadmap Beyond ITER

Premières réalisation

Réacteurs actuels

Réacteurs avancés

Systèmes du futur



1950 1970 1990 2010 2030 2050 2070 2090

Generation FINALISER

UNGG
Magnox

Generation EXPLOITE

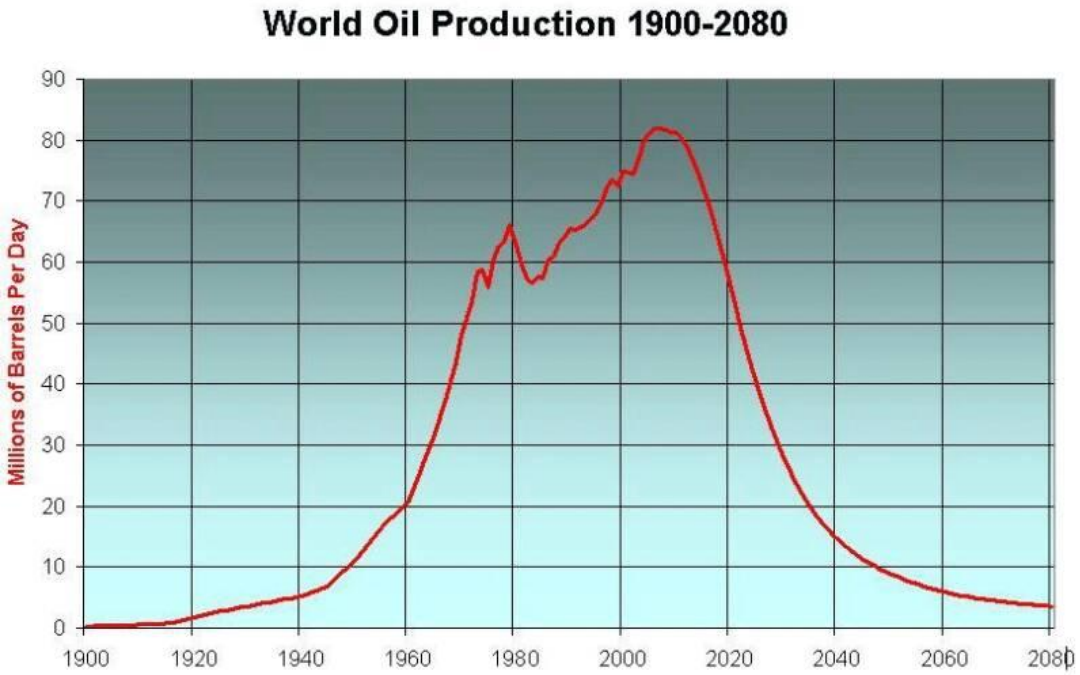
REP 900
REP 1300
N4 (1450)

Generation III OPTIMISER

EPR (1600)
GT-MHR, PBMR

Generation IV CONCEVOIR

ITER – a Global Challenge



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