FUSION FOR ENERGY

Nuclear Fusion: One Energy Option for the Future

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Geosciences Information for Teachers Workshop

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Energy: what are the options?

- There are several energy sources with substantial potential to supply energy in the future:

Fossil fuels	Renewables
Fission	Fusion

- Each has both advantages and disadvantages
  - Safety issues
  - Environment (CO_2, waste)
  - Large scale potential
  - Availability of fuels and dependence on imports
  - Economics and social acceptability

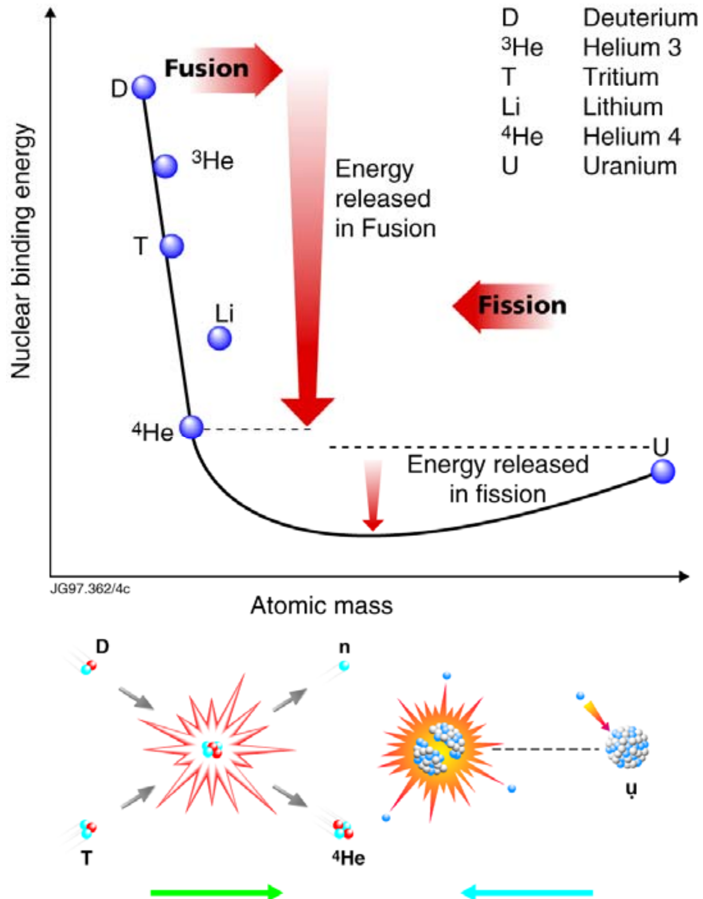
⇒The issue of energy supply is so important that all potential options should be developed

⇒ **AND SAVE ENERGY !!**

What is fusion ?

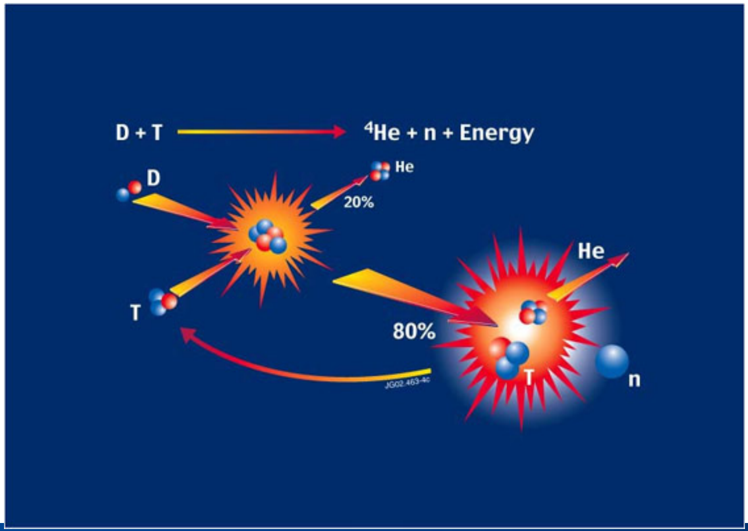
- **When nuclei of light atoms collide at very high energy they fuse and release an amount of energy much higher than the spent one**

- **Deuterium (D) + Tritium (T) is the “easiest” fusion reaction**



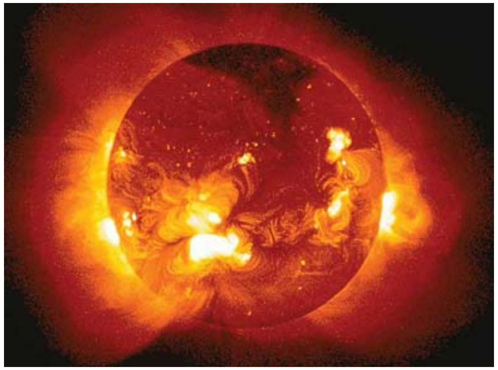
- **Fuels are largely available: Deuterium is extracted from water**

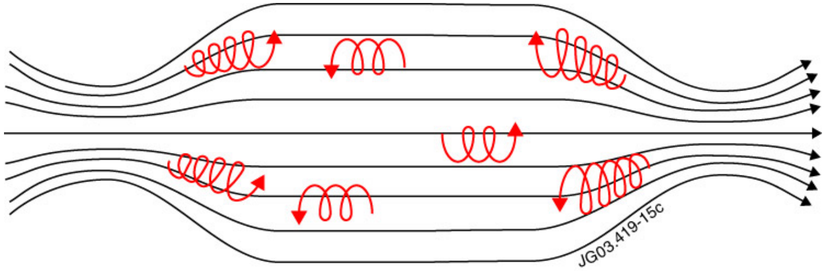
  Tritium is produced inside the reactor from Lithium

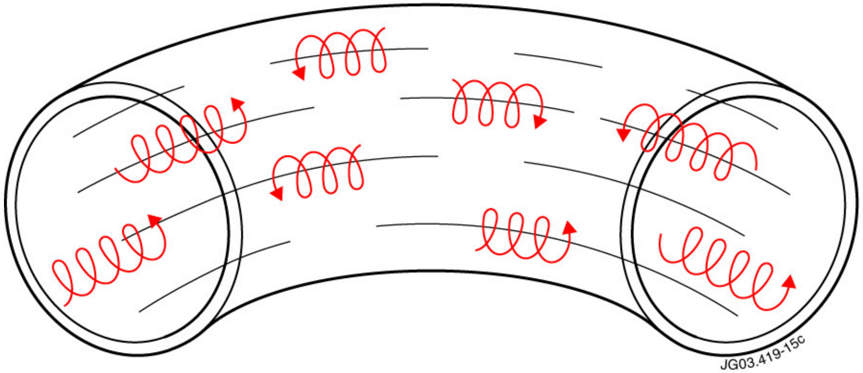


How does fusion work?

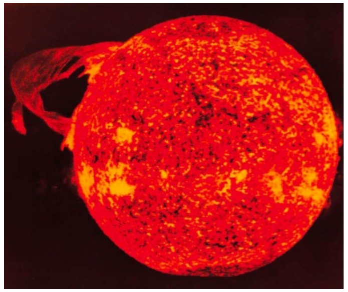
- In the core of the sun or a star fusion happens at a temperature of about 10 million degrees
- In fusion machines the reactions can happen above 100 million degrees.
- A way to confine the plasma is to use strong magnetic fields that create a “cage” preventing the particles to touch the walls of the “container”.
- To avoid the losses at the end of the “container” a closed, toroidal configuration is used

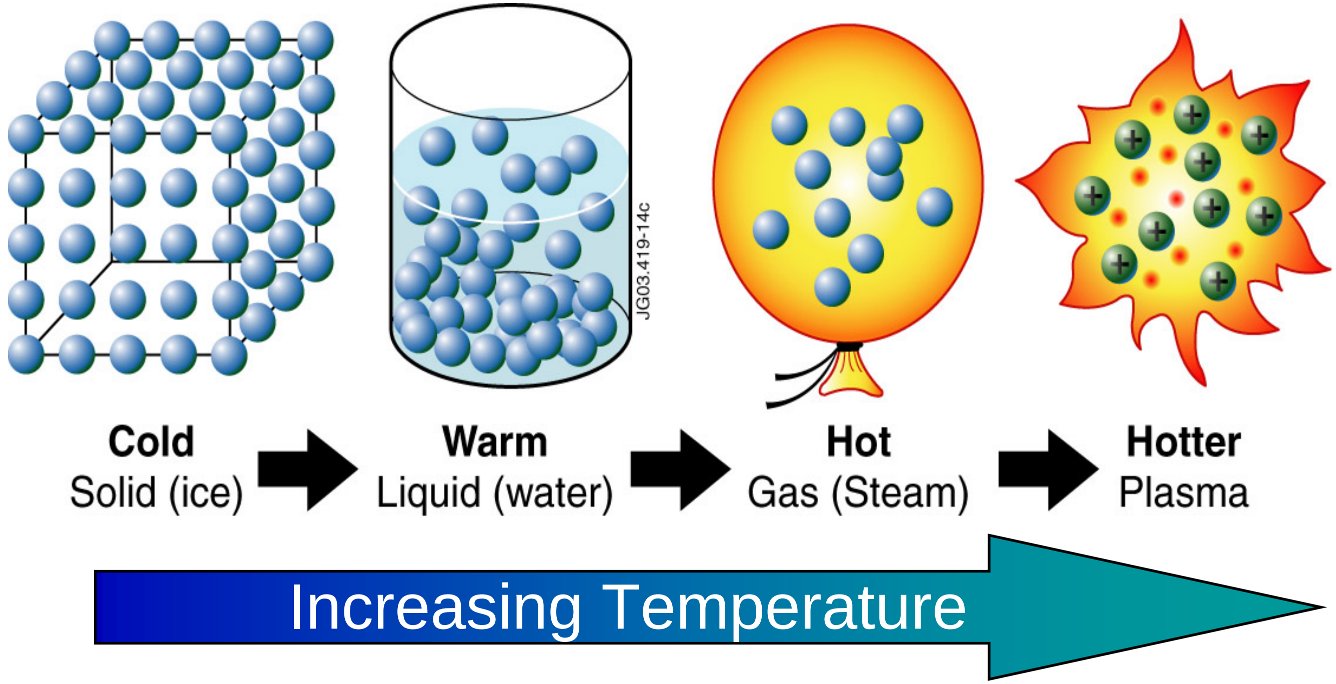






Plasma : the 4th state of matter





A plasma is made of electrically charged particles, but it is globally neutral.

Conditions to sustain reaction

For the reaction to propagate, conditions must be maintained.

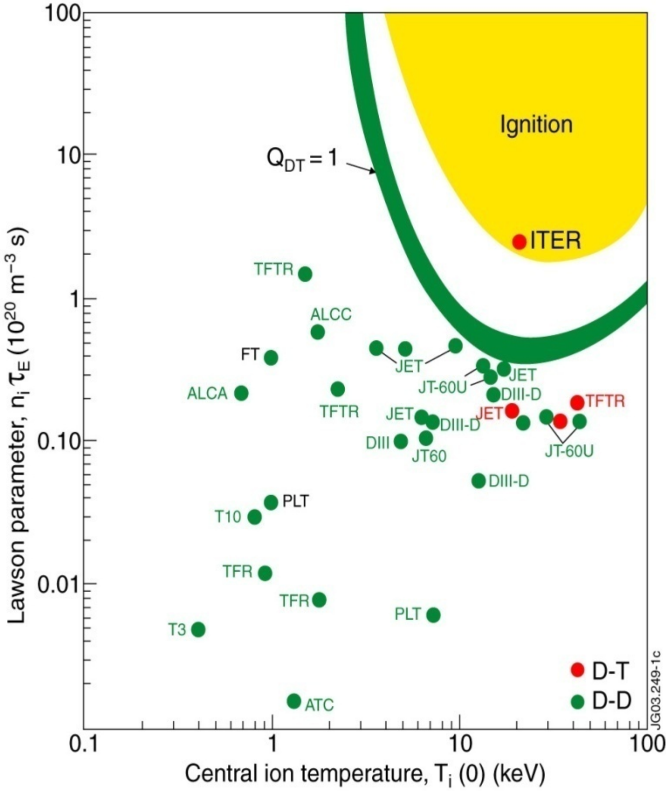
Power must be large enough to compensate for the losses

n (density) x τ_E (confinement time) > function of T (Temperature)

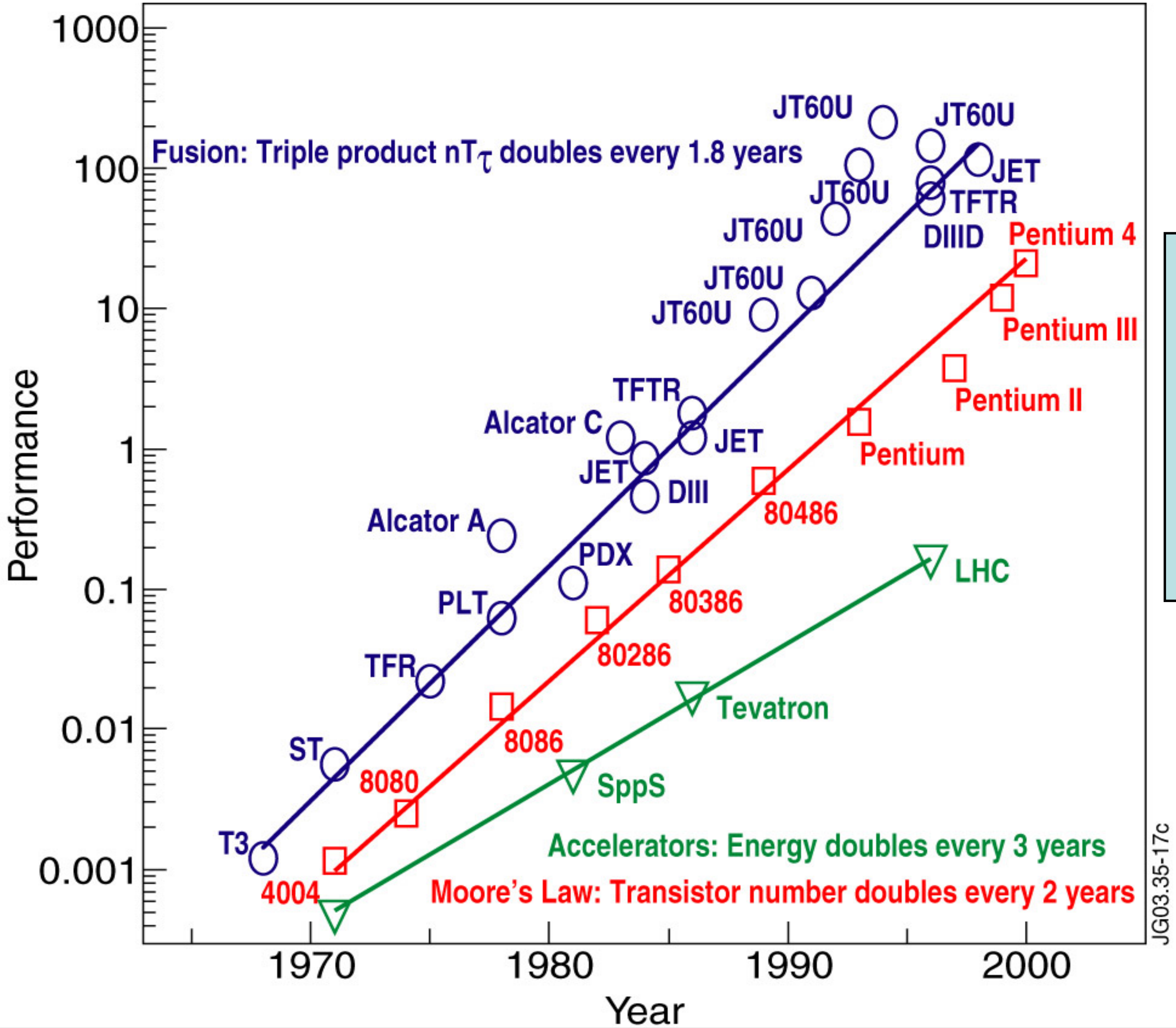
Lawson Criterium:

$n \times \tau_E \times T > 10^{21}$ (m^{-3} s keV)

τ_E is a measure of how fast the plasma looses its energy



Progress Rate in Fusion Research

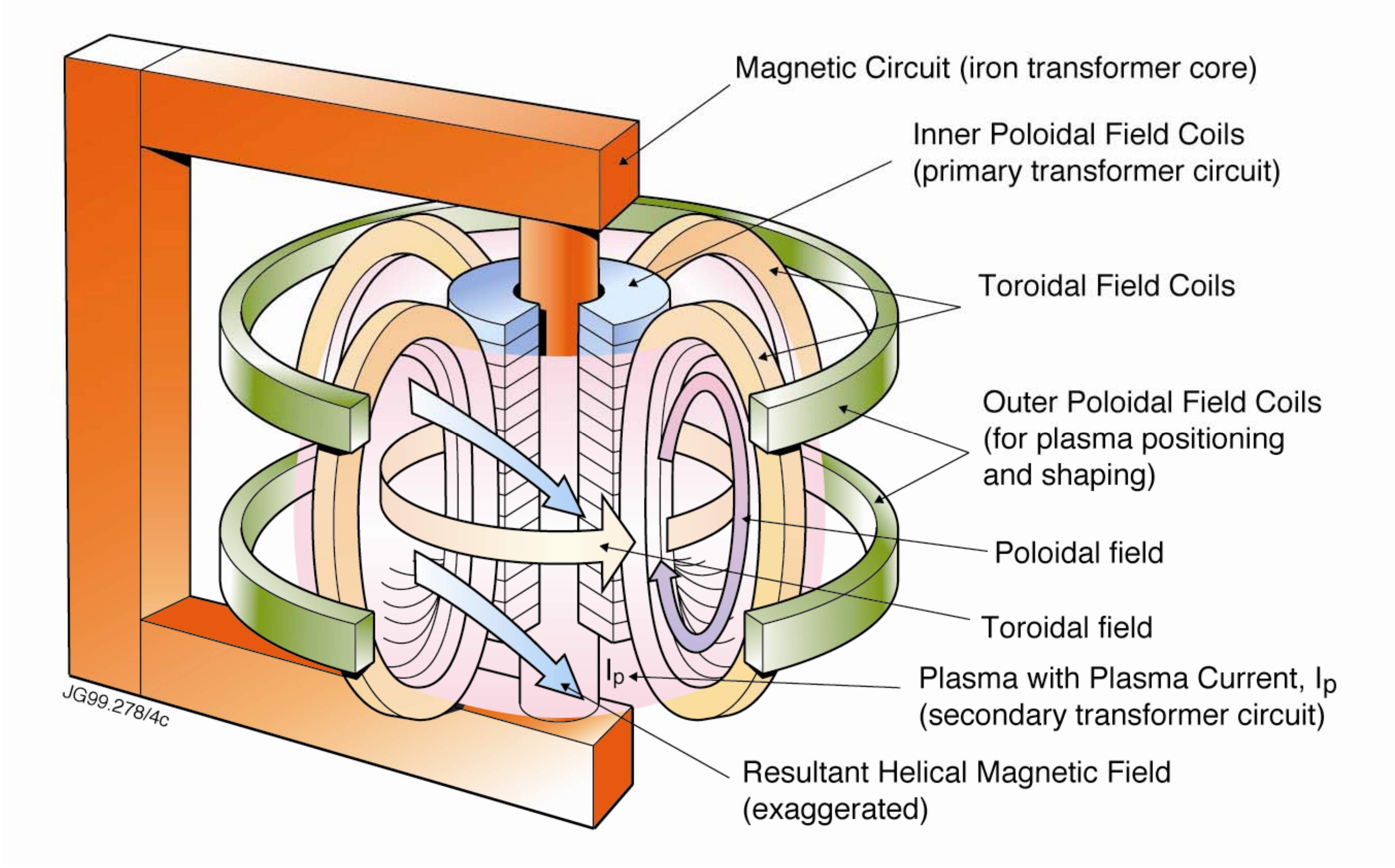


Evolution of the performance over the years matches that of computers "Moore's law"

What are the merits of fusion?

- **Fusion will be a large source of energy with basic fuels largely available in the sea**
- **No greenhouse gas emissions. Very low impact on the environment**
- **A fusion power station would not require the transport of radioactive materials**
- **Power Stations would be inherently safe. No possibility of "meltdown" or "runaway reactions". Fusion reactors work like a gas burner: once the fuel supply is closed, the reaction stops**
- **No long-lasting radioactive waste to create a burden on future generations**
- **With about 3000 m^3 of water (->D) and 10 tons of Li ore (->T), a future 1 GW_{el} fusion power plant will be able to operate one year**

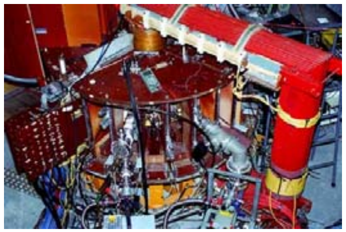
The Tokamak



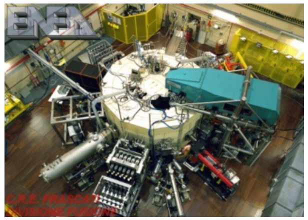
Magnetic Circuit (iron transformer core)
Inner Poloidal Field Coils
(primary transformer circuit)
Toroidal Field Coils
Outer Poloidal Field Coils
(for plasma positioning
and shaping)
Poloidal field
Toroidal field
Plasma with Plasma Current, Ip
(secondary transformer circuit)
Resultant Helical Magnetic Field
(exaggerated)
Ip
JG99.278/4c

FUSION FOR ENERGY

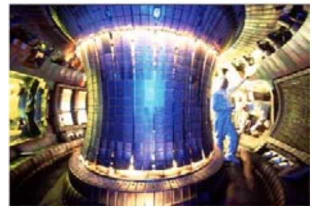
Fusion = Collaboration



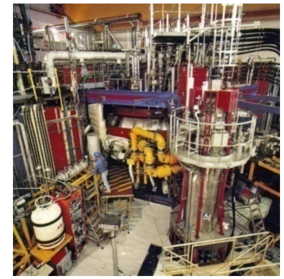
ISTTOK



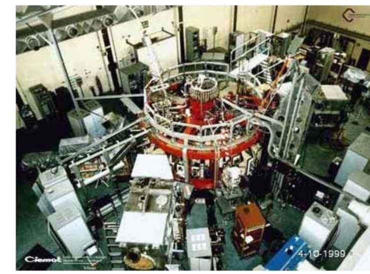
FTU



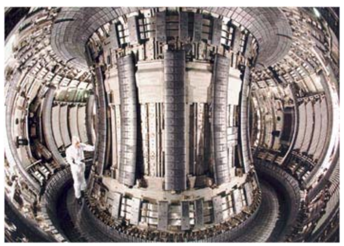
Asdex-UG



TORE SUPRA

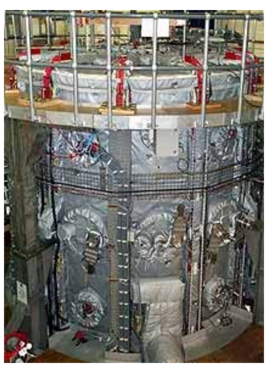


TJ-II

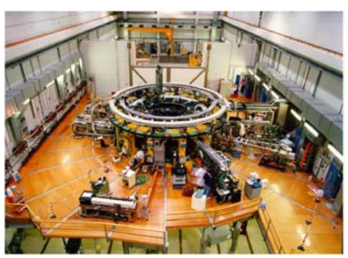


JET

Wendelstein 7-X

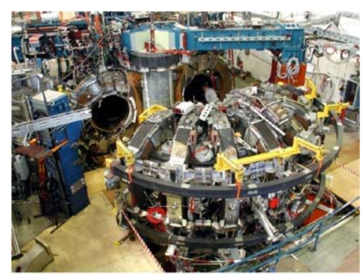


MAST



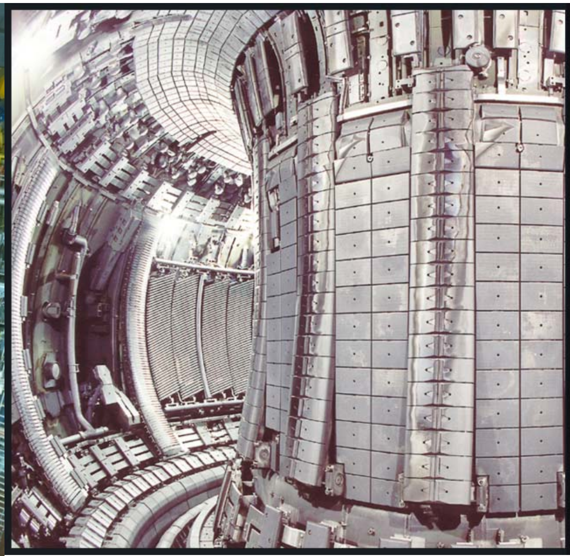
RFX

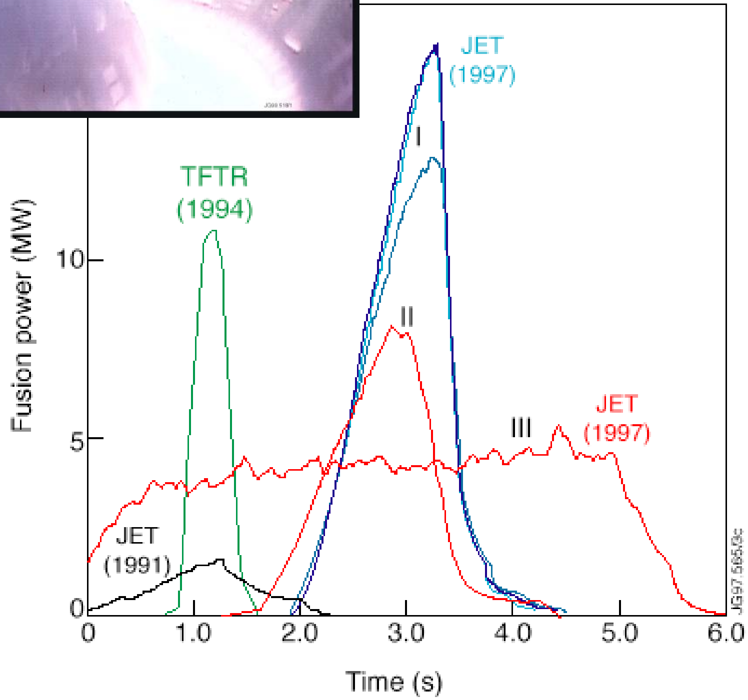
TCV



TEXTOR

From JET …

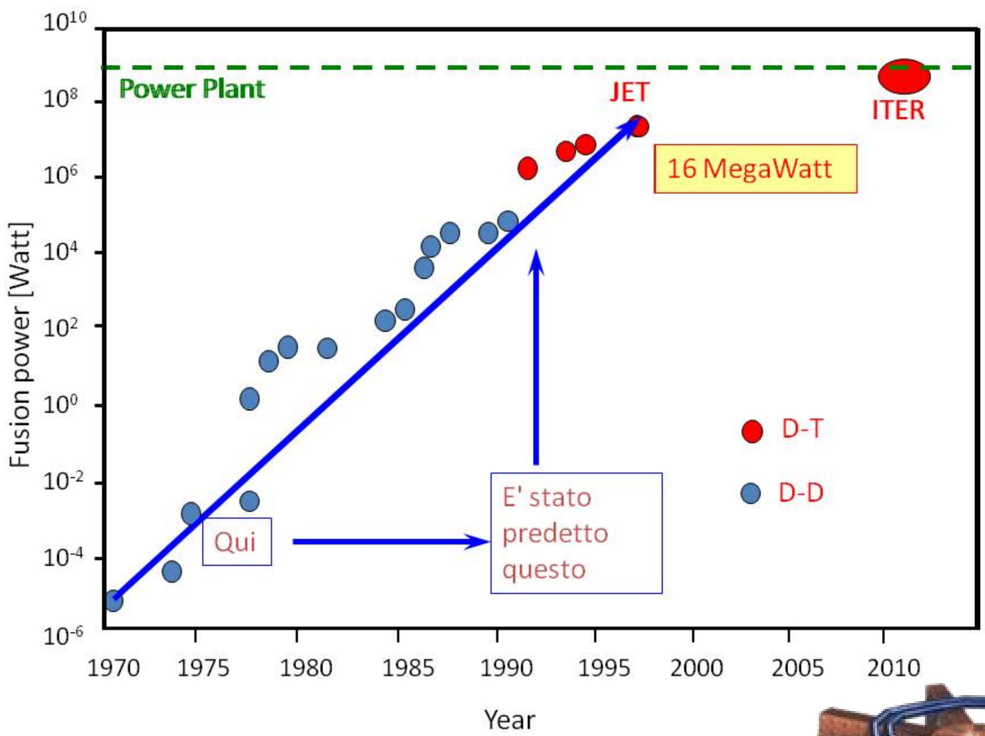




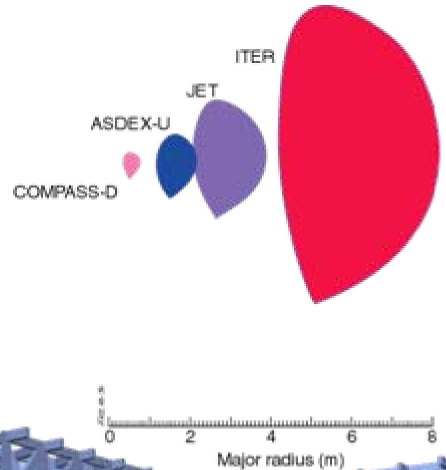
In 1997 (50% D+50% T) JET achieved three records:

- **Fusion Power: 16 MW**
- **Fusion Energy: 22 MJ**
- **Ratio generated power to supplied power: Q=0.64**

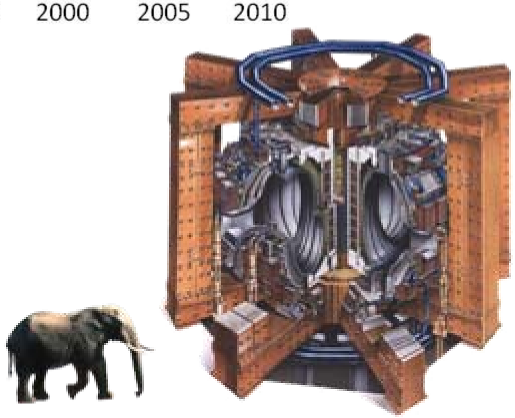
… to ITER

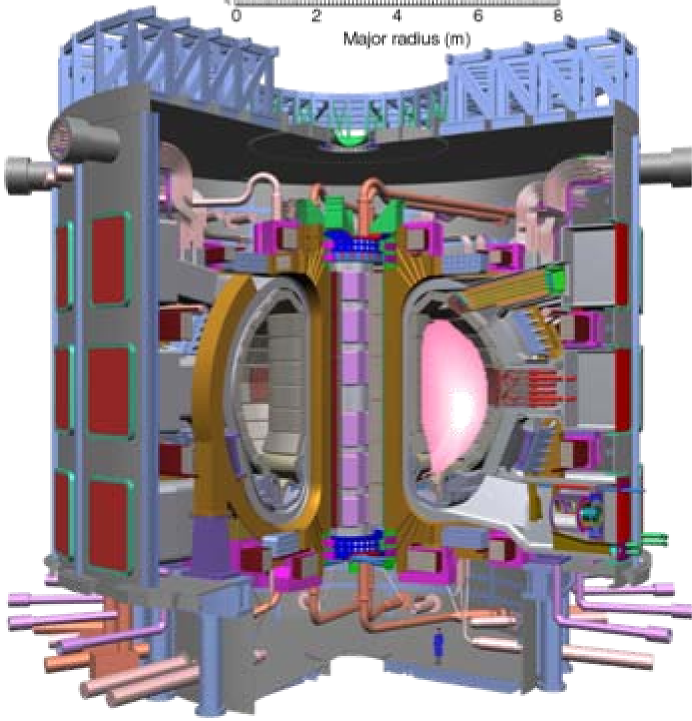


Power Plant
JET
ITER
16 MegaWatt
Fusion power [Watt]
Year
Qui
E' stato predetto questo
D-T
D-D
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
1970
1975
1980
1985
1990
1995
2000
2005
2010



ITER
JET
ASDEX-U
COMPASS-D
0
2
4
6
8
Major radius (m)





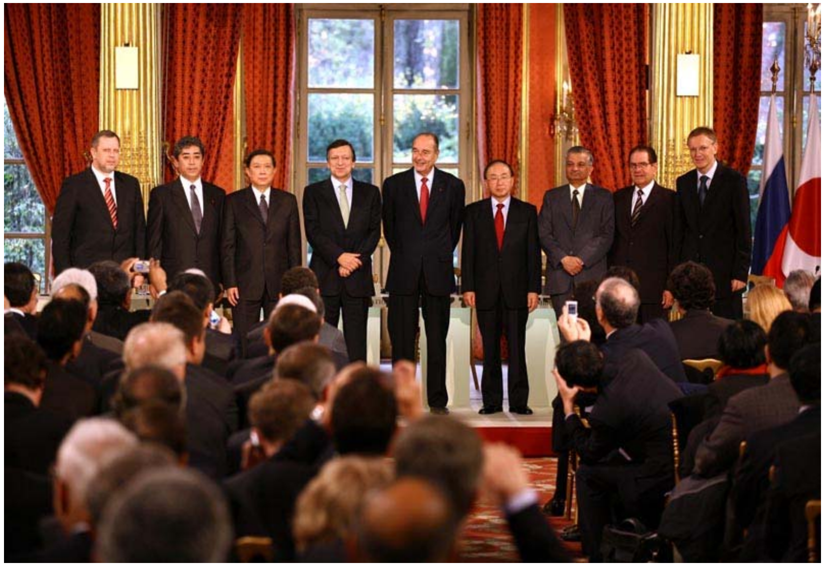
ITER

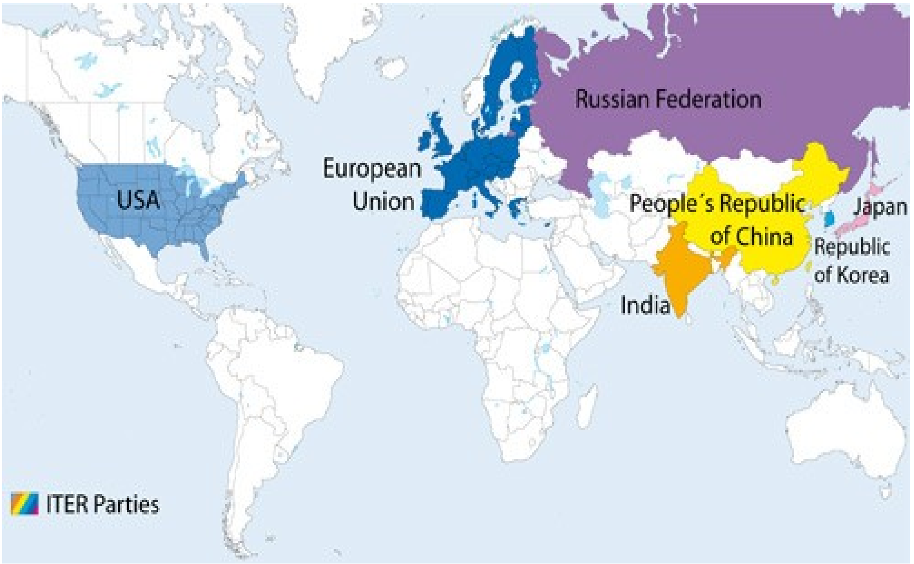
ITER – A brief History

- **An international collaboration between Europe, Japan, Russia, and (until mid 1999) the United States**
- **The Engineering Design Activities finished in July 2001. The detailed design was approved by the ITER Parties**
- **Negotiations between the Parties on "joint implementation" started in 2002**
- **The USA, China and Korea joined the negotiations in 2003. India followed later.**
- **Cadarache (F) chosen as construction site (June 2005).**

The ITER Agreement

- **Involvement of 7 parties representing over half of the world's population – the largest R&D project ever!**
- **ITER Agreement signed in Paris on 21 November 2006**





ITER Parameters

Plasma Current (MA)	**15**
Toroidal Magnetic Field on Axis (T)	**5.3**
Machine Height (m)	**26**
Machine Diameter (m)	**29**
Plasma Volume (m^3)	**837**

Operation Phase: about 20 years

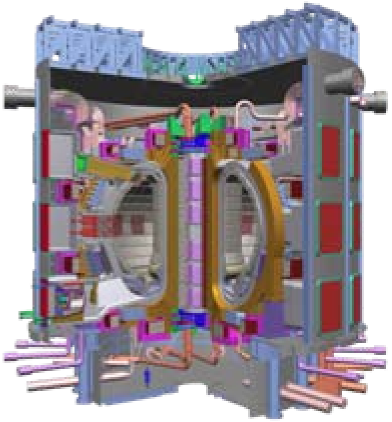
Technical aims of ITER

Demonstrate

- **steady state fusion power production**
- **technologies required for fusion power stations**

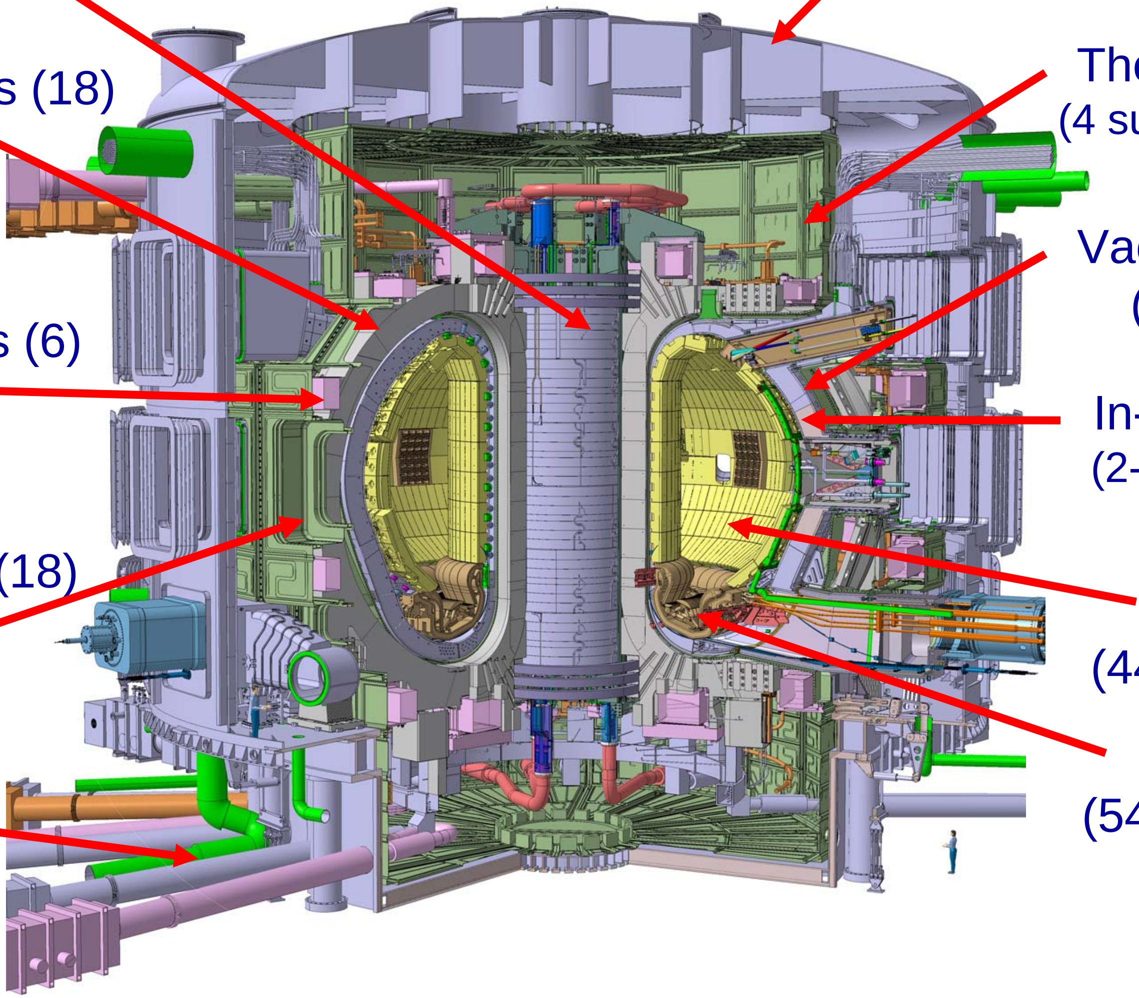
Study and optimise plasma behaviour.

Produce about 500 MW of fusion power with a Power Amplification (Ratio Total Fusion Power/Input Power to the Plasma) ≥10

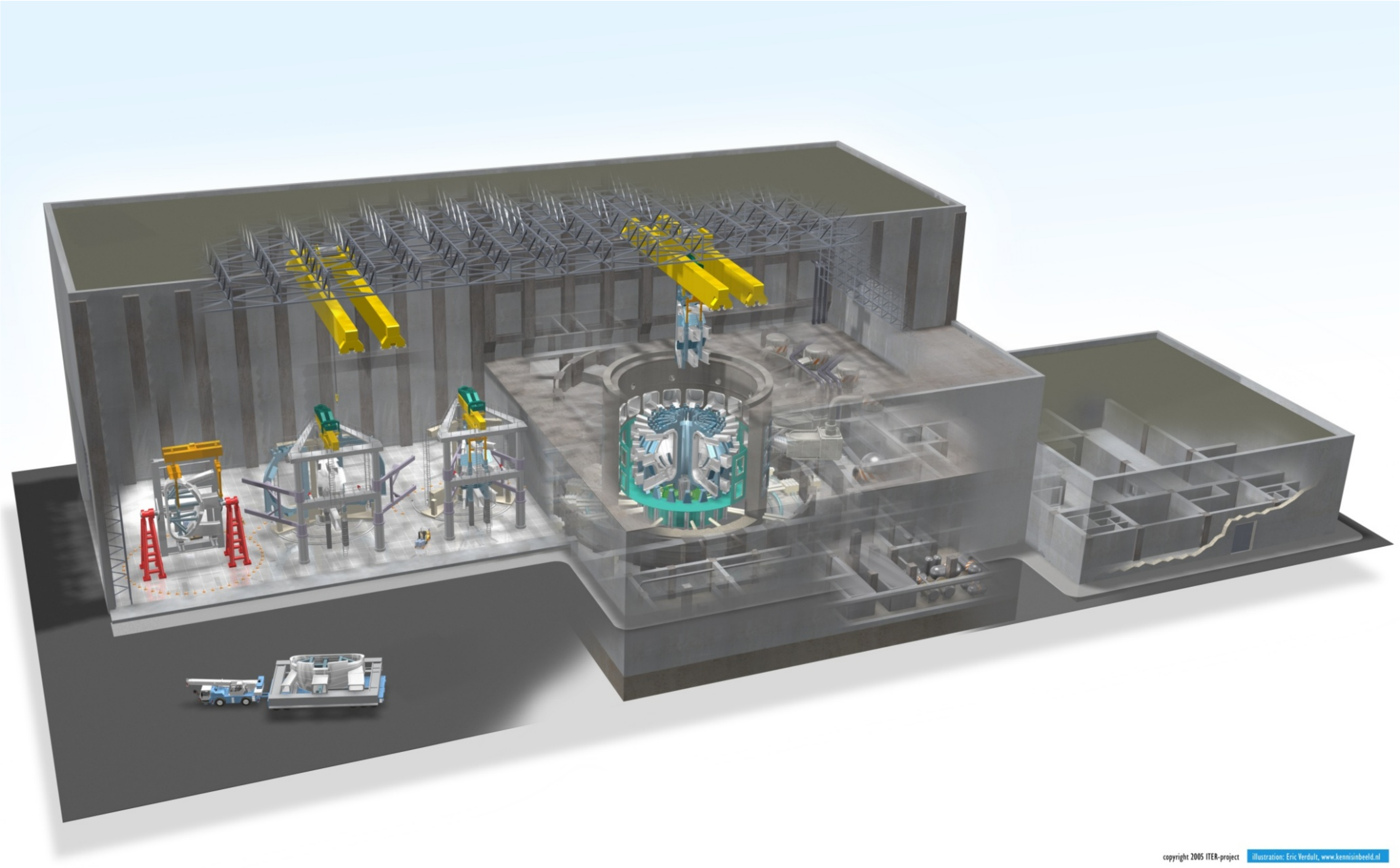


The ITER Machine

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



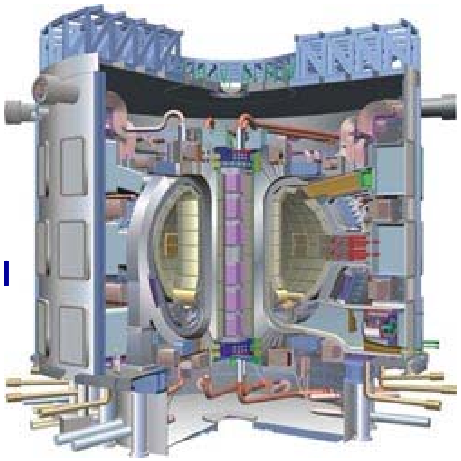
The Tokamak Building



ITER-Quick Mass Comparison

Courtesy of G. Johnson, IO

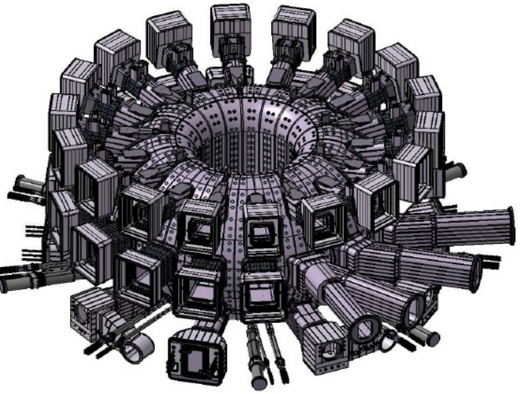
ITER Machine



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

Charles de Gaulle Aircraft Carrier:
~38000 t (empty)
261 m long (Commissioned 2001)

Vacuum Vessel:

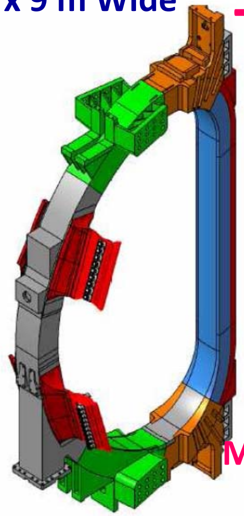


VV & In-vessel components mass:
~8000 t
19.4 m outside diameter x 11.3 m tall

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

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

TF Coils:



Jumbo B747-300
Max take off weight ~356 t

The ITER Design and Technology has been underpinned by R&D

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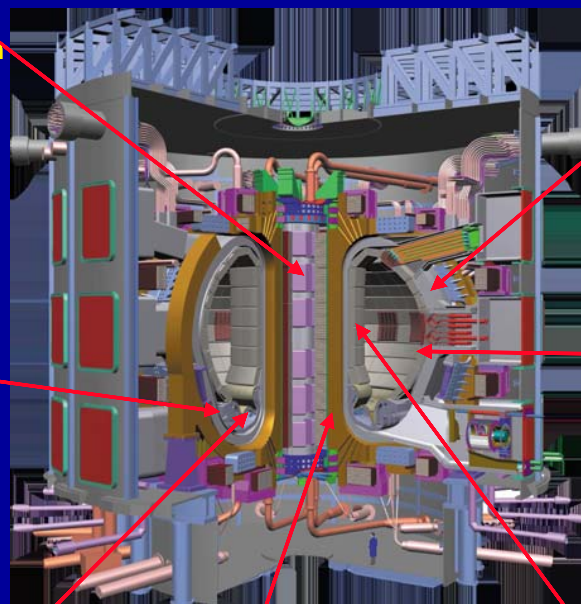
Completed R&D Activities by July 2001.

CENTRAL SOLENOID MODEL COIL

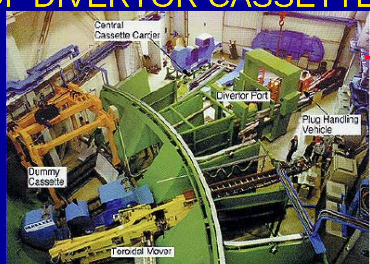
Radius 3.5 m
Height 2.8m
B_{max}=13 T
W = 640 MJ
0.6 T/sec

VACUUM VESSEL SECTOR

Double-Wall, Tolerance ±5 mm



REMOTE MAINTENANCE OF DIVERTOR CASSETTE



Attachment Tolerance ± 2 mm

BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

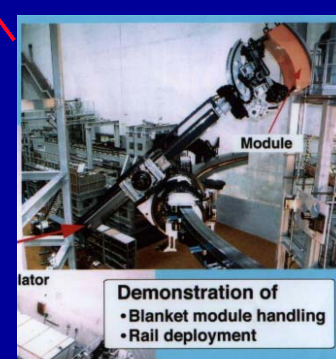
DIVERTOR CASSETTE

Heat Flux >15 MW/m^2, CFC/W

TOROIDAL FIELD MODEL COIL

Height 4 m
Width 3 m
B_{max}=7.8 T
I_{max} = 80kA

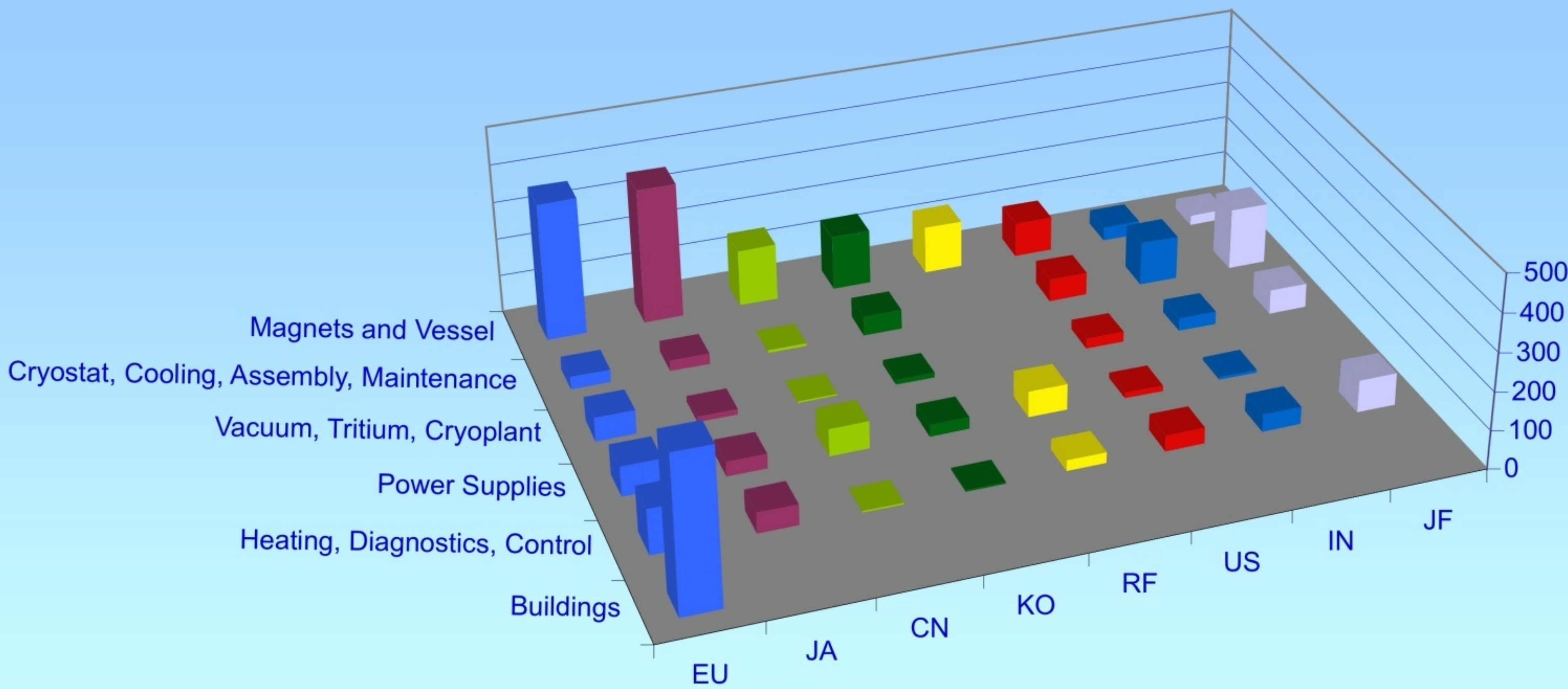
REMOTE MAINTENANCE OF BLANKET



4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

Construction Cost Sharing

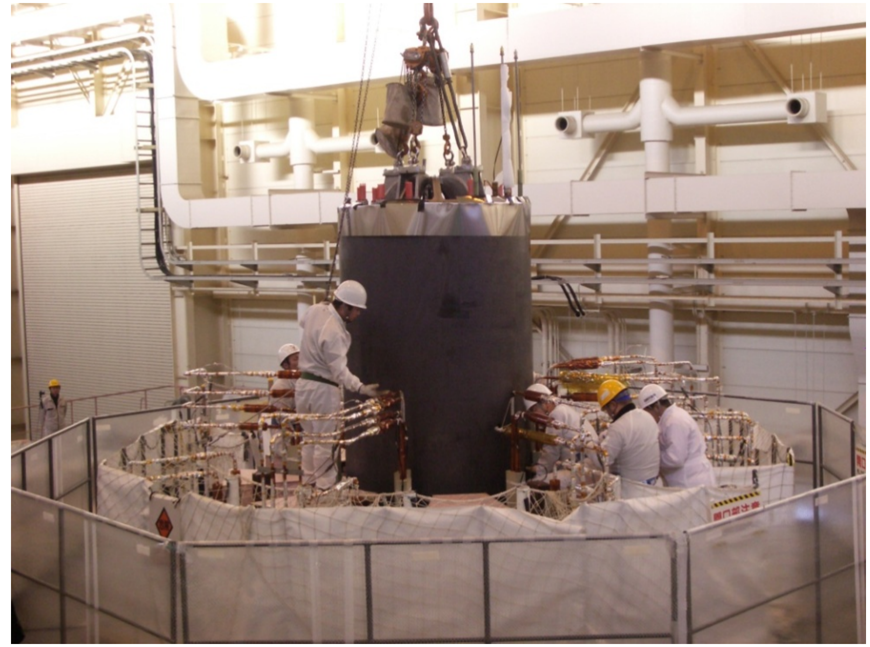
Some procurement packages will be shared among several Parties:



R&D for ITER - 1

Courtesy of ENEA

Sub-scale pre-compression ring tests show rupture stress of ~1,400 MPa, well above the limit required by ITER



Courtesy of JAEA

The Poloidal Field Coil Insert successfully tested in Naka (J). Stable operation of the test coil up to 52 kA at 6.4 T and 4.5 K.

Courtesy of CEA

EU First Wall qualification mock-up tested with no indication of failure observed.

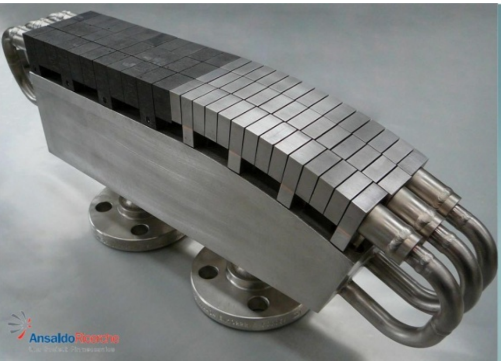
R&D for ITER - 2

Construction of a full-sized, 20 Tons VV Poloidal Sector Prototype successfully completed within required VV tolerances (+/- 10 mm)

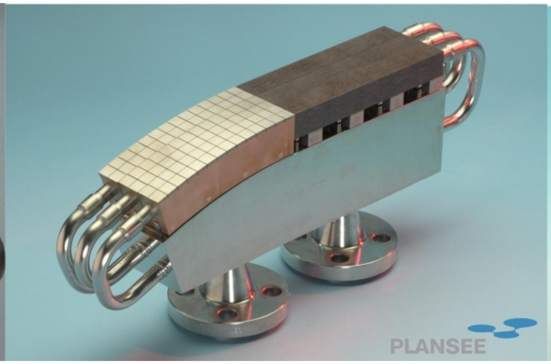
Courtesy of DCNS

VV: 6.2 metre long e-beam welds Successfully completed

Courtesy of Ansaldo



Courtesy Ansaldo



Courtesy Plansee

Divertor CFC armours passed qualification tests at 20 MW/m^2.

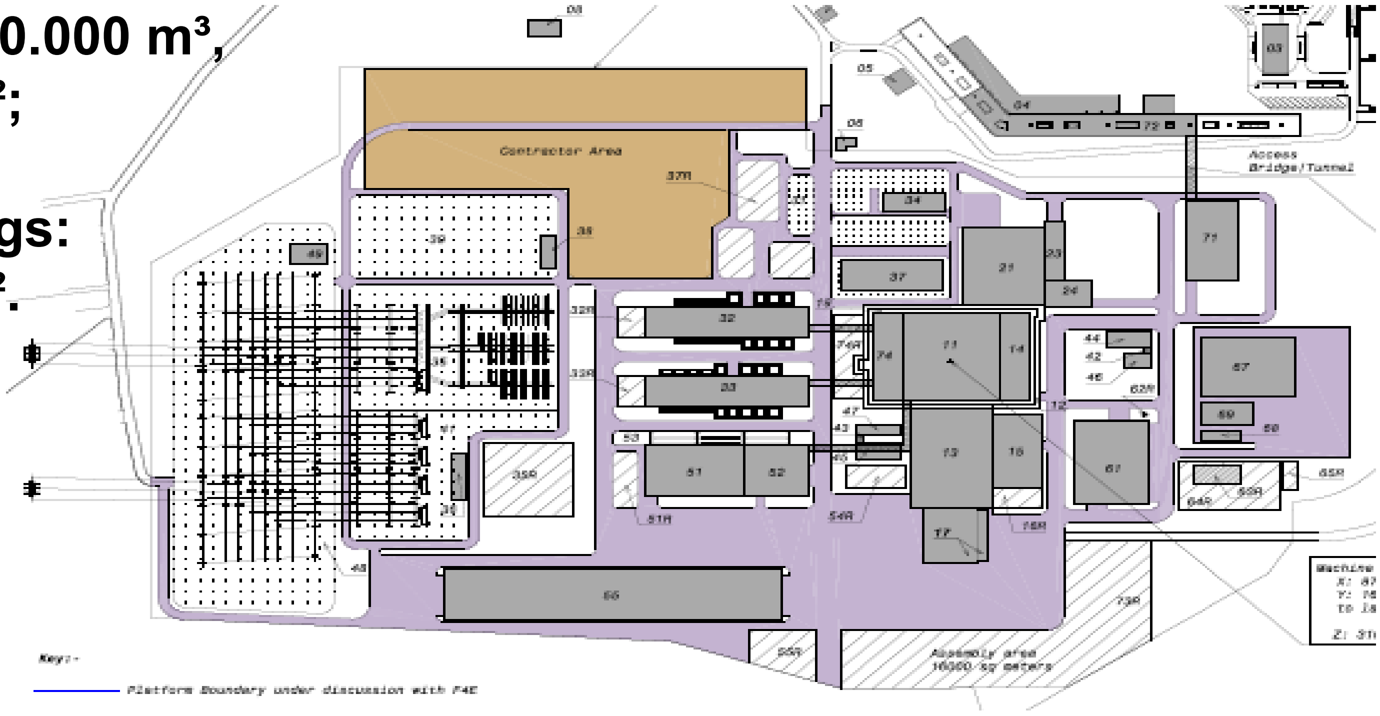
FUSION FOR ENERGY

Buildings - Procurements

ITER Buildings form an integrated complex extending over an area of about 50 hectares, including 28 buildings.

Reinforced concrete buildings and selected infrastructure: 250.000 m³ of concrete, building volume 750.000 m³, foot print 21.000 m²;

Steel frame buildings: foot print 29.000 m².



Buildings & Site

Site Leveling is completed and Excavations are about to start

European Fusion Development Programme - 1

- **Aim**: demonstration of scientific, technological and economic feasibility of fusion power. That is, provide all information required by a Utility to decide to build a first Fusion Power Plant (FPP).
- **Power plant-oriented strategy** confirmed in 1990/1996/2000 by Fusion Programme Evaluation Boards. Identied steps: JET-ITER-DEMO-PROTO.
- **Fast Track** approach introduced at the end of 2001: investigate the possibility of merging two steps, DEMO and PROTO, and operating IFMIF (international fusion materials irradiation facility) in parallel to ITER.

European Fusion Development Programme - 2

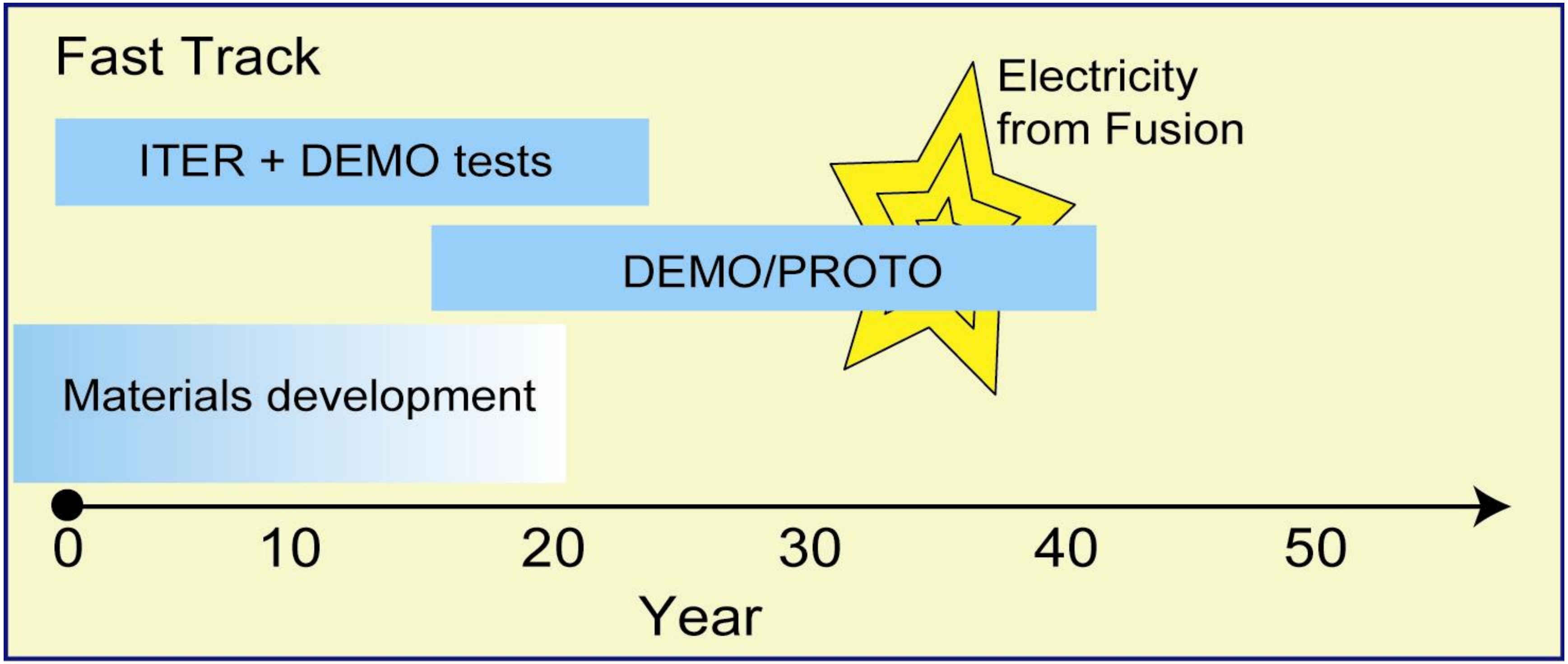
- **Knowledge required to build the first FPP:**
  - **Proven physics basis**
  - **Qualified components and processes**
  - **Proof of compliance with safety and environmental requirements**
  - **Proof of economic viability**

ITER

DEMO

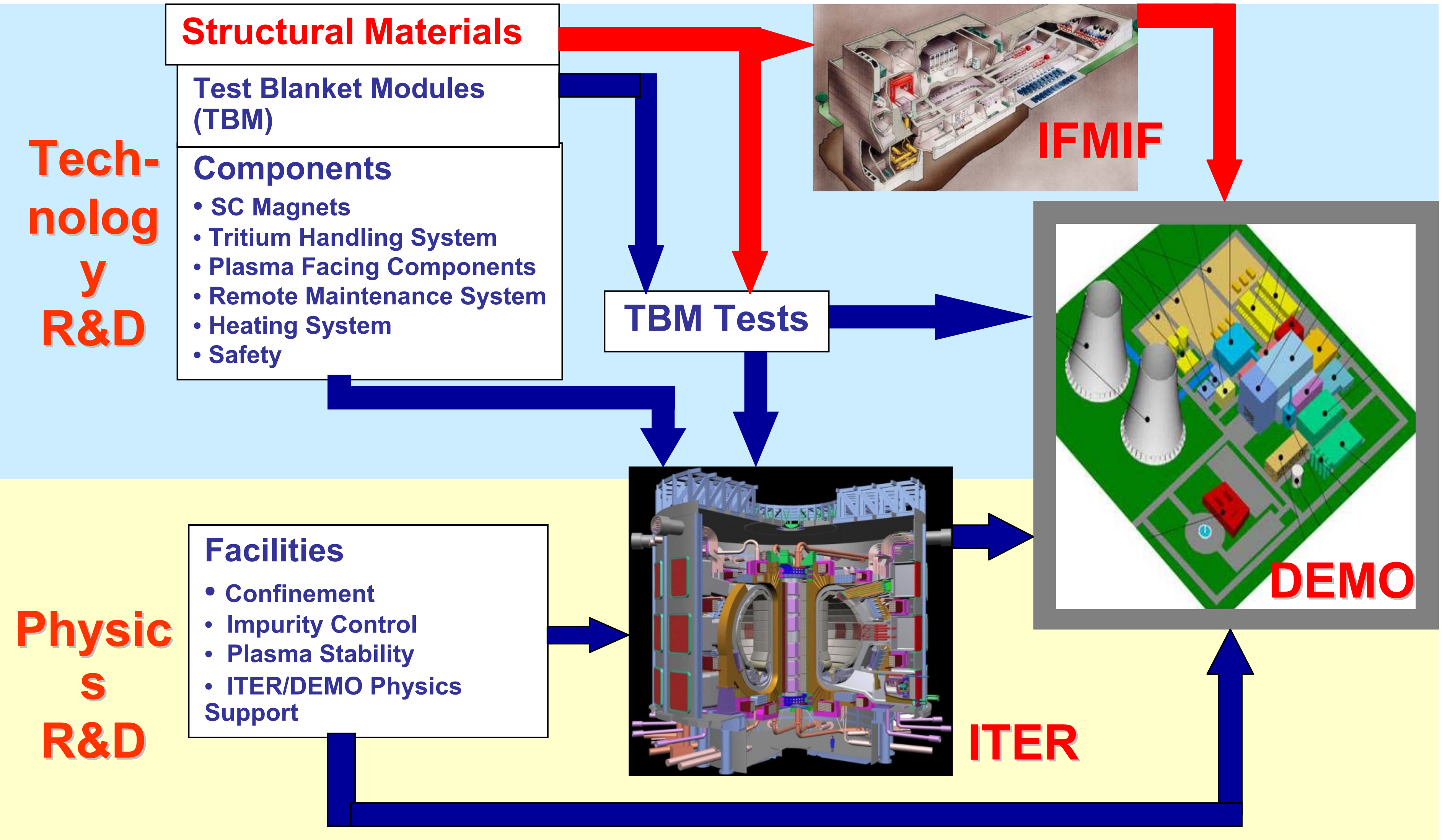
- **A component or process will be qualified after operation in reactor relevant conditions for a duration comparable to its expected lifetime.**

Roadmap to electricity production by fusion



FUSION FOR ENERGY

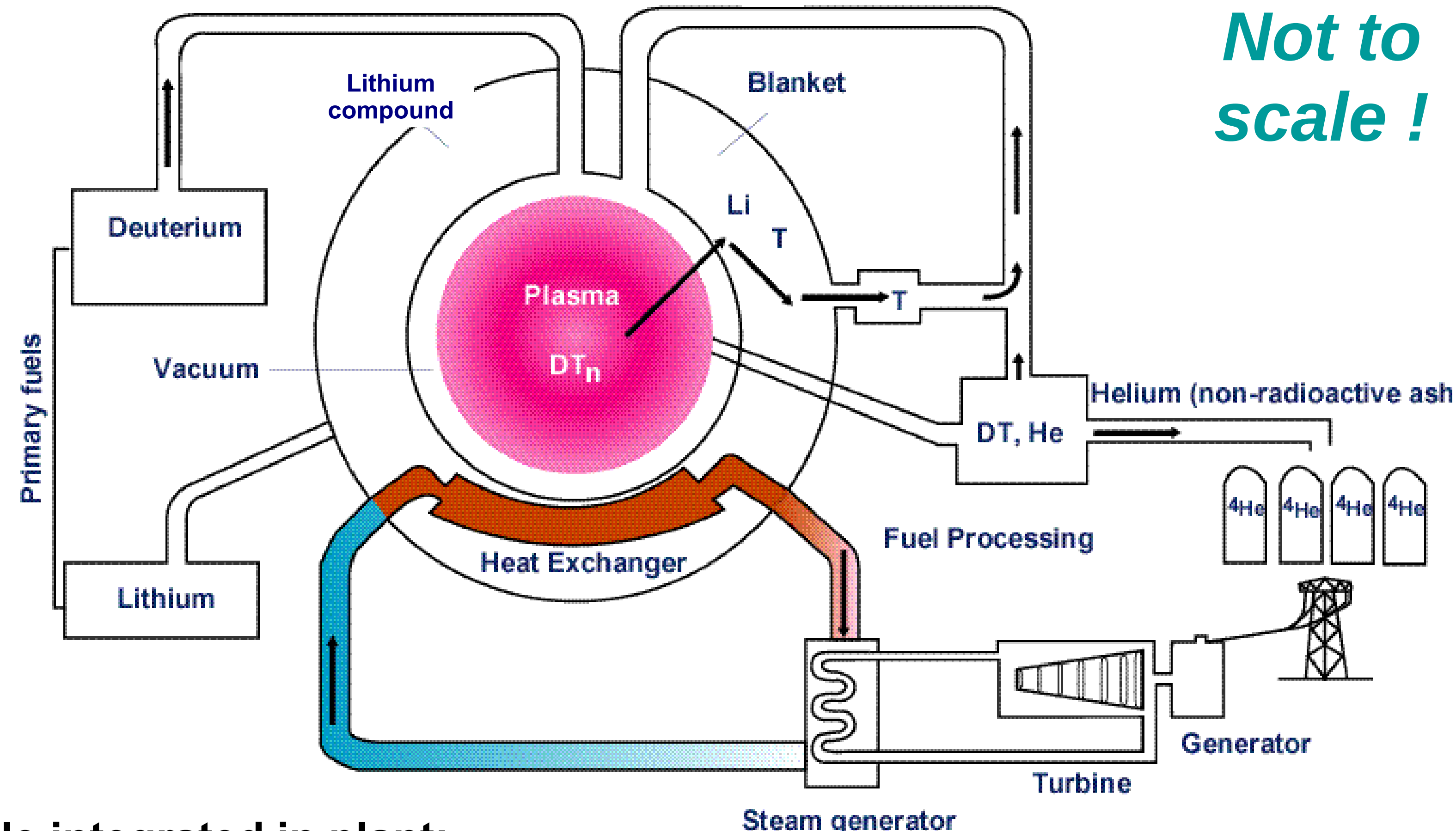
Path to DEMO



Fuel Cycle in Fusion Plant

Our final goal: a Fusion Power Plant (FPP)

Not to scale !



Fuel cycle integrated in plant:

D and Li as basic fuel, T bred in-plant by neutron-Li reactions

“Fusion Energy will be ready when mankind will need it"

Lev Andreevich Artsimovich (1909-1973)

[inventor of the Tokamak]

More Information

www.fusionforenergy.europa.eu

www.efda.org

www.jet.efda.org

www.iter.org

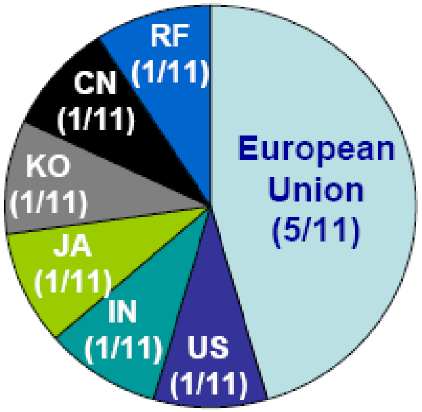
FUSION FOR ENERGY

THANK YOU FOR YOUR ATTENTION

BACK-UP SLIDES

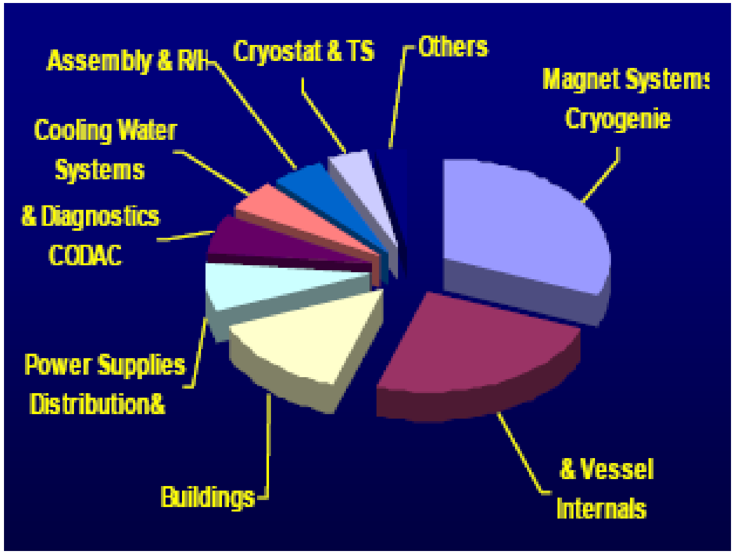
ITER Cost Breakdown
(normalised to credit allocation in kIUA)

- **Construction Cost:**
- Total procurement value : 3021 kIUA*
- Staff: 477 kIUA
- R&D: 80 kIUA
- **Total amount: 3578 kIUA (5.365 M€/ 2008)**
- Overall contingency : 358 kIUA(10% of total)



- **Operations Cost (20 yrs):** 188 kIUA/ y

- **Deactivation and Decommissioning:** 281 + 530 kIUA



* IUA: ITER Units of Account1 IUA is equivalent to 1 kUS$ in 1989