# JET and ITER and the future of fusion research

*Jef ONGENA*
*ERM-KMS and JET*
*IIHE – Brussels*
*ULB-VUB*
*Brussels 1 April 2011*

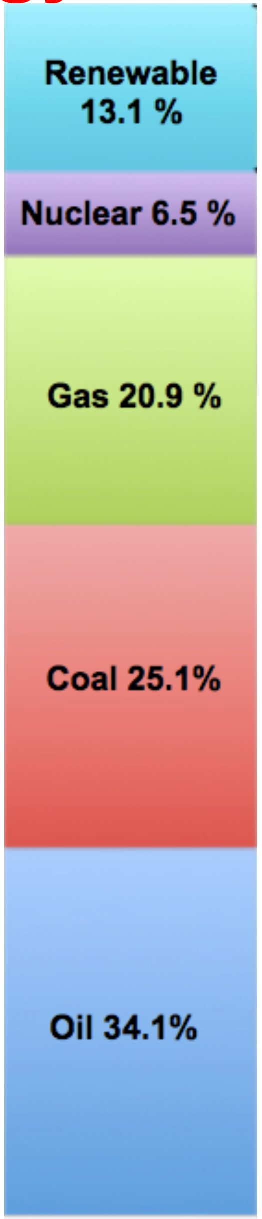
## *Content of the talk*

*I. Why fusion research ?*

*II. How to realise fusion on earth and current status*
- *a. Tokamak - Stellarator*
- *b. The largest tokamak in the world : JET*
- *c. The next step : ITER*

*III. Conclusions*

# Primary Energy Now : > 80% from fossile sources




Non-fossile energy : total 19.6 %

Fossile energy : total 80.4 %

**Source :**
**"Renewables in Global Energy Supply"**
**IEA Fact Sheet 2007**
**www.iea.org**

# $CO_2$ concentration in the atmosphere for the last 1000 years

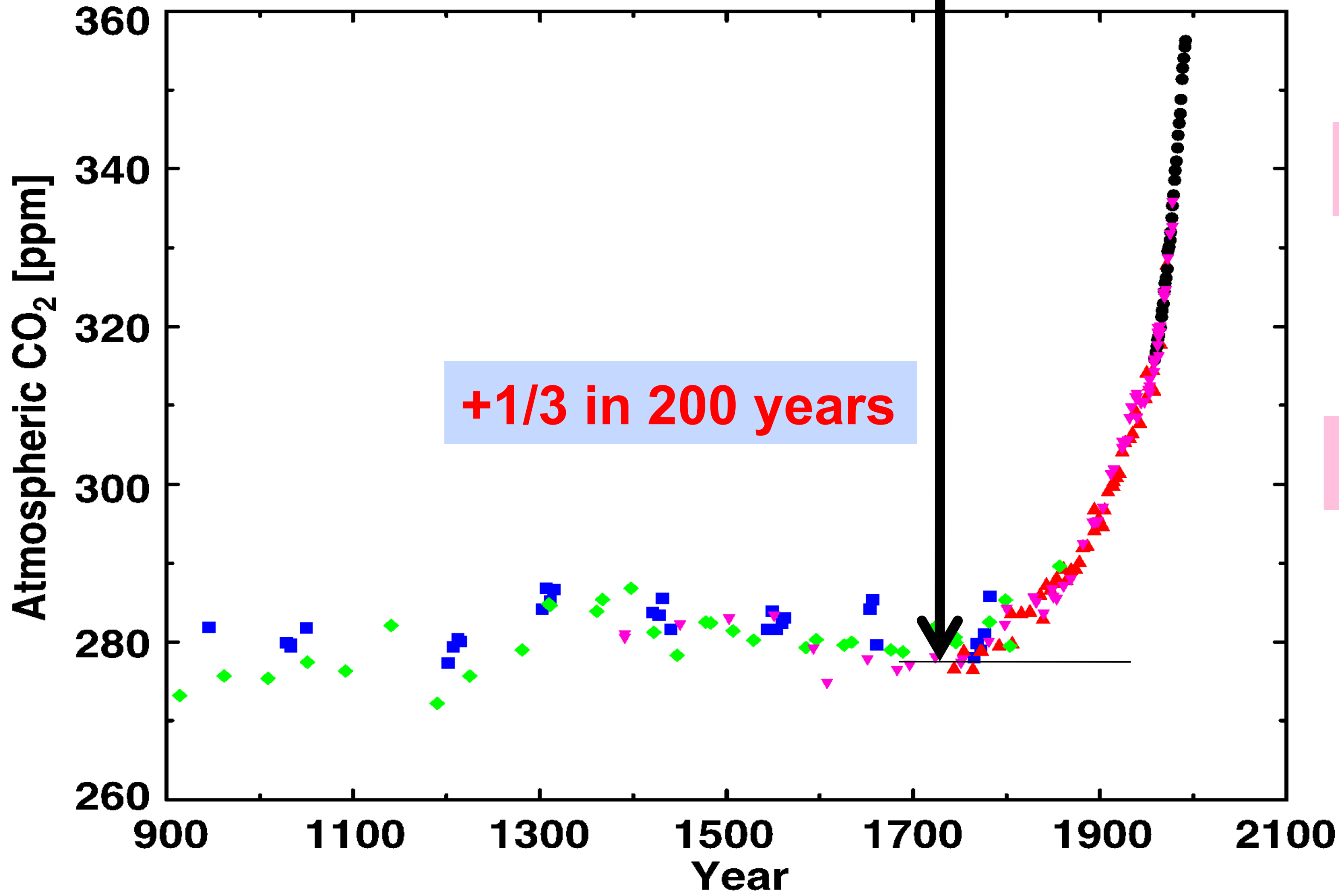
2008
385ppm

+30ppm
in 12 years

1996
355ppm

+30ppm
in 26 years

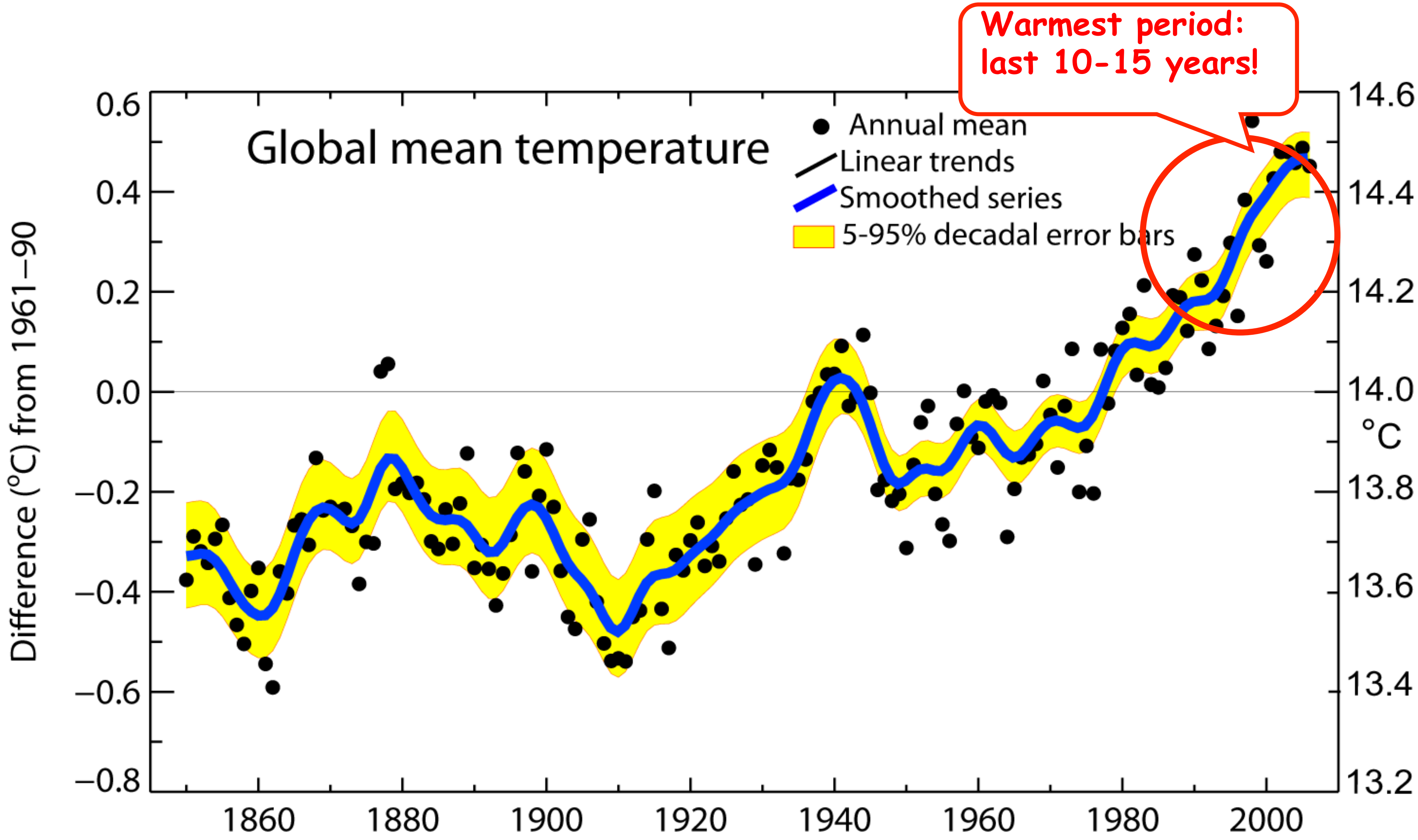
1970
325ppm




+45ppm
in 170 years

1800
280ppm

# Observed change in global mean temperature on earth




# Global Oil Depletion

An assessment of the evidence for a near-term peak in global oil production

October 2009

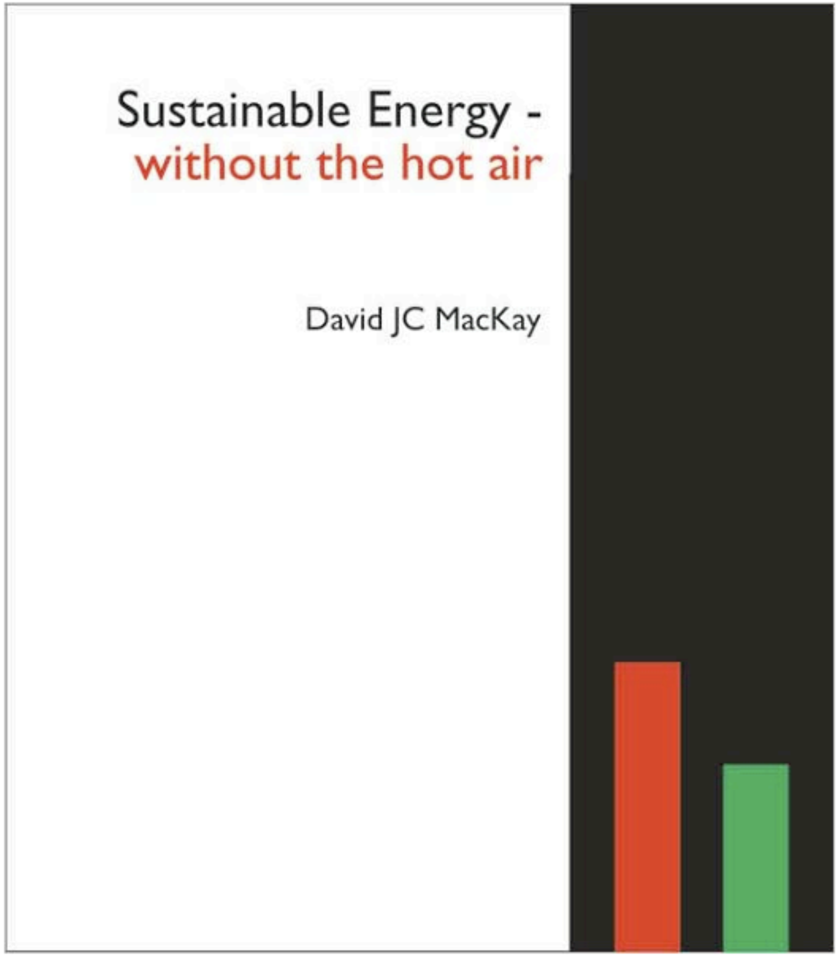
Vrije download op
http://www.ukerc.ac.uk/support/Global%20Oil%20Depletion

# The risks presented by oil depletion deserve serious attention

- Many forecasting methods are overly pessimistic
- But forecasts that delay the peak beyond 2030 requires assumptions that are at best optimistic and at worst implausible
- There is a significant risk of a peak before 2020
- This is not distant, in view of the lead times to develop alternatives

UKERC

# Very strongly recommended




*Physics Dept. Cambridge University, UK (2009)*
*Free download (and lots more) on www.withouthotair.com*

# Current and Future energy needs

## Average Total Power Consumption 2006 (per capita)

- United States : 11300 W
- EU and Japan : 5000-5500 W
- Developing Countries : 0-1000 W
- World Average : 2400 W

## Annual Total World Energy Consumption

**6.5 billion people x 2400 W per capita x 1 year**
**= 15.6 TWyr**

# Current and Future energy needs

## Expected Annual Total World Energy Consumption in 50 years :

Assumptions :

1. 10 billion people in 50 years
2. World Average energy consumption : 3000 W
   (Only 1/4 of what average USA person uses now !)

in 50 years, we could possibly expect :

**10 billion people x 3000 W per capita x 1 year**

**= 30 TWyr**

**More than twice the present energy use !!!**

# Current and Future energy needs

## From the previous slide : ~15TW needed in 50 years

15000GW/50years = 300GW/year =

**~ every day 1 GW more during 50 years...**

Consequences :

1. Hopefully not with coal, gas .... ?
2. If yes, effects of CO2 ?
3. Possible ? probably: in 2008 China alone +7GW/month!
4. Heavy Pollution: North Pacific Hg content +30% last 20 yr !

**World needs urgently good alternatives to fossil fuels !!**

# Colossal task for the next 50 years

**Doubling of existing capacity**
**and**
**Converting existing capacity from fossil to non-fossil (80%)**

**i.e.**

**20000-30000 GW in new energy systems...**

**No option can be excluded !**

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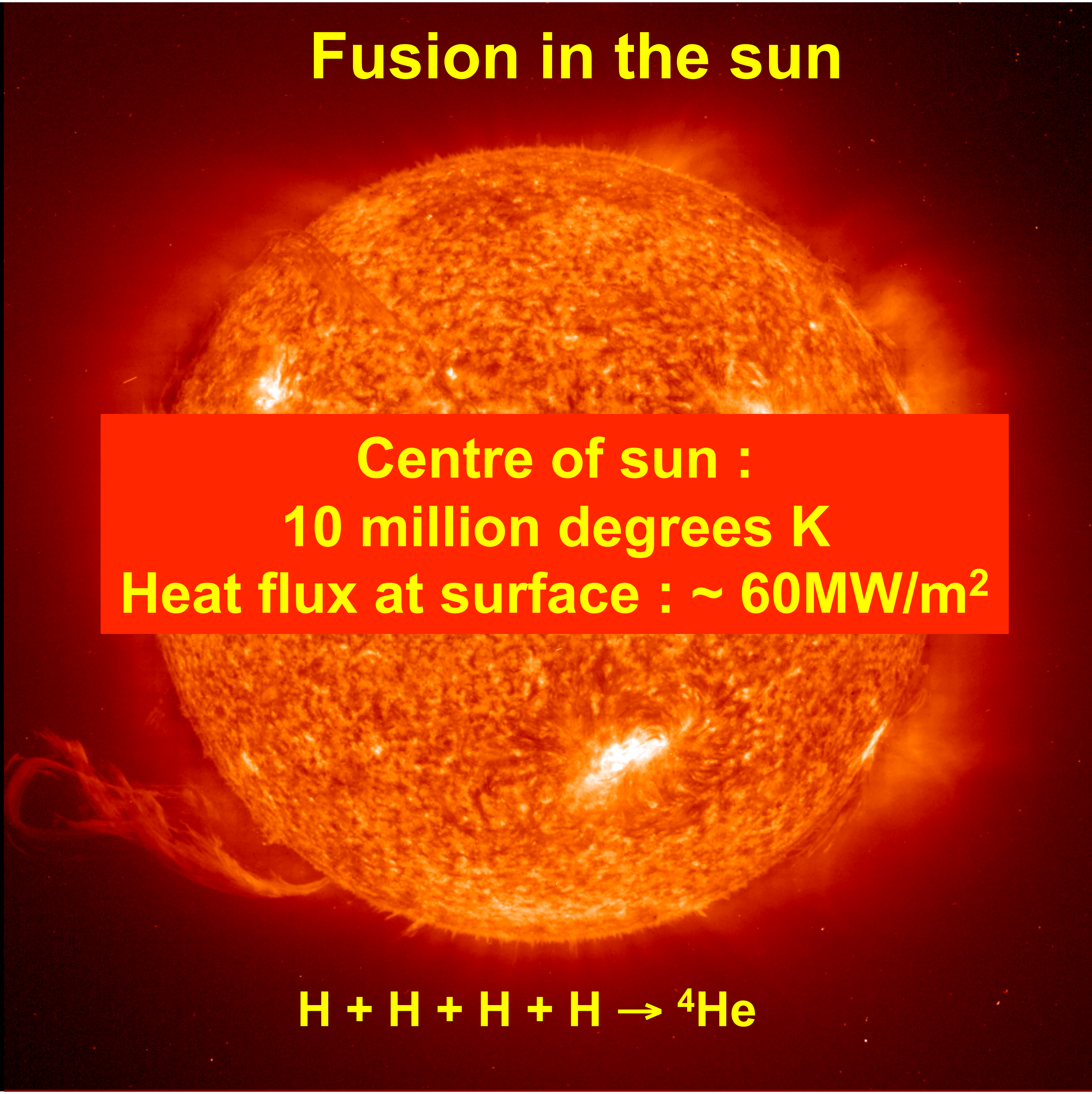
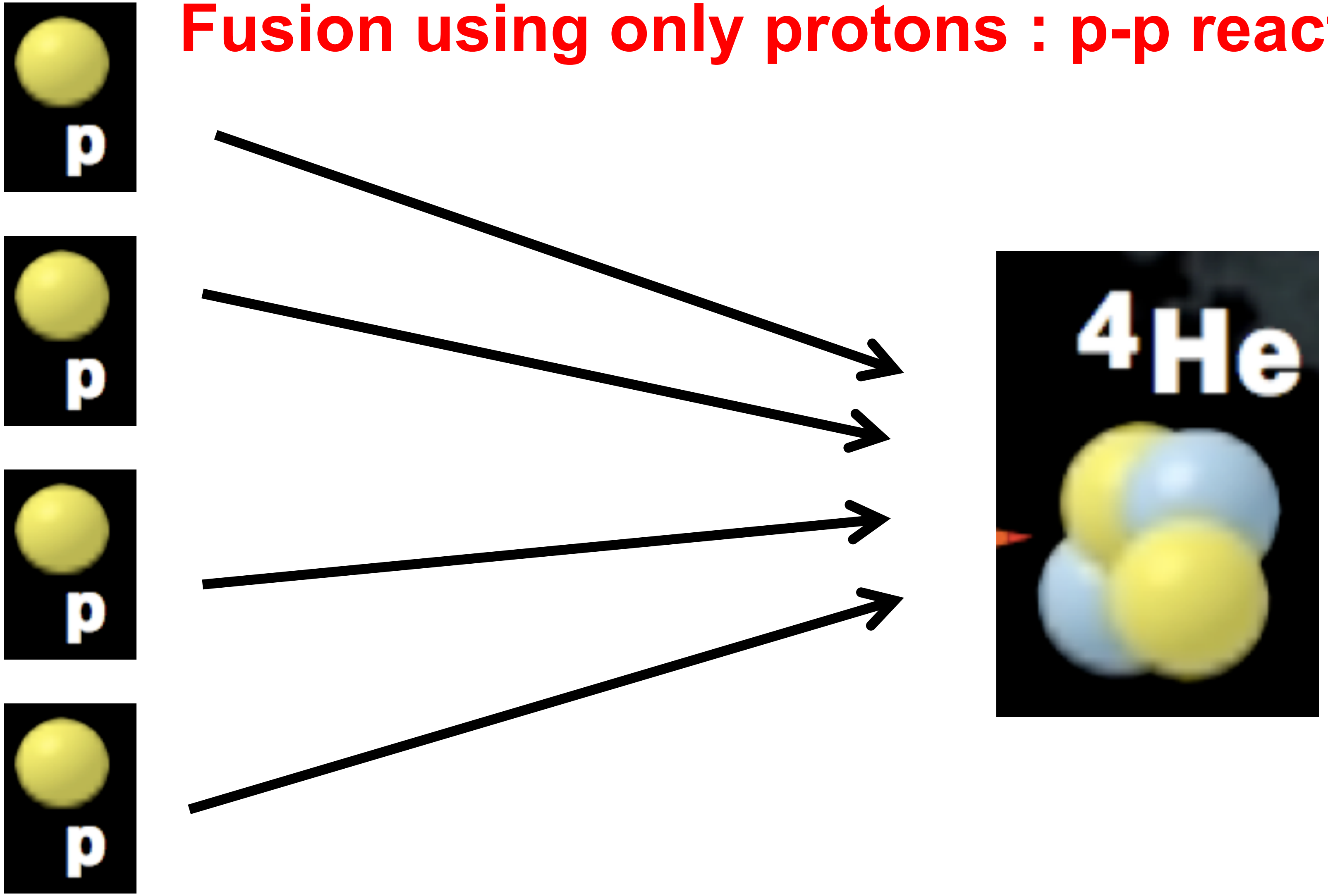
- ***c. The next step : ITER***

***III. Conclusions***


Fusion in the sun
Centre of sun :
10 million degrees K
Heat flux at surface : ~ 60MW/m$^2$
H + H + H + H → $^4$He

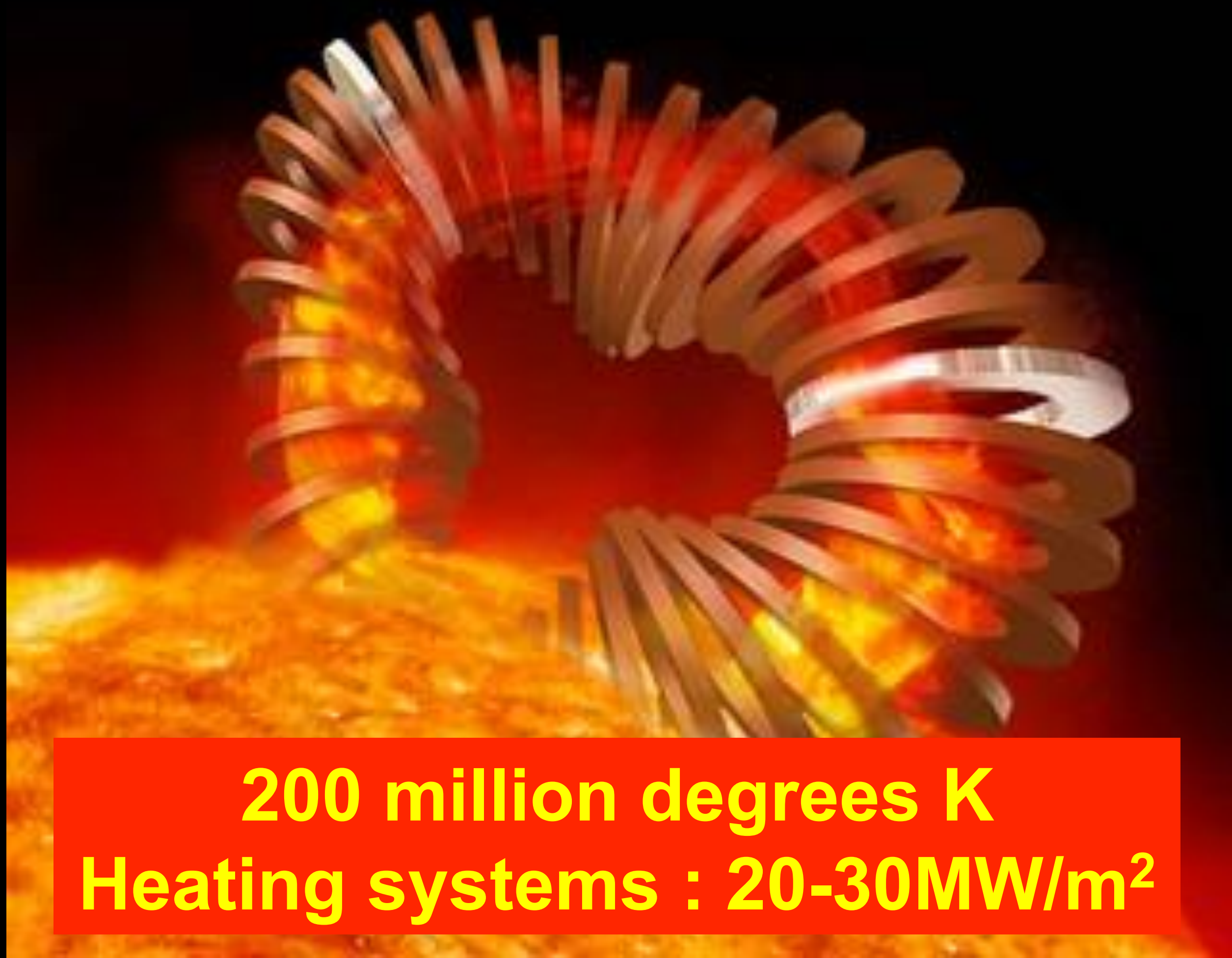
# Fusion using only protons : p-p reaction




**Very small reaction rate ...**

**But ... every second 4 million tons of H → $^{4}$He + energy !**

# Fusion in the lab



**200 million degrees K**

**Heating systems : 20-30MW/m$^2$**

# 'Easiest' fusion reactions

| Fusion Reaction | | Temperature (in million degrees) | Energy (in keV) |
|---|---|---|---|
| D + T | $^4He$ + n | 100-200 | 17,600 |
| D + $^3He$ | $^4He$ + p | ~700 | 18,300 |
| D + D | $^3He$ + n | ~800 | ~4,000 |
| | T + p | ~800 | ~4,000 |

# Tritium production for D-T reaction

$$\checkmark \quad D + T \rightarrow {}^{4}He + n + \Delta E$$

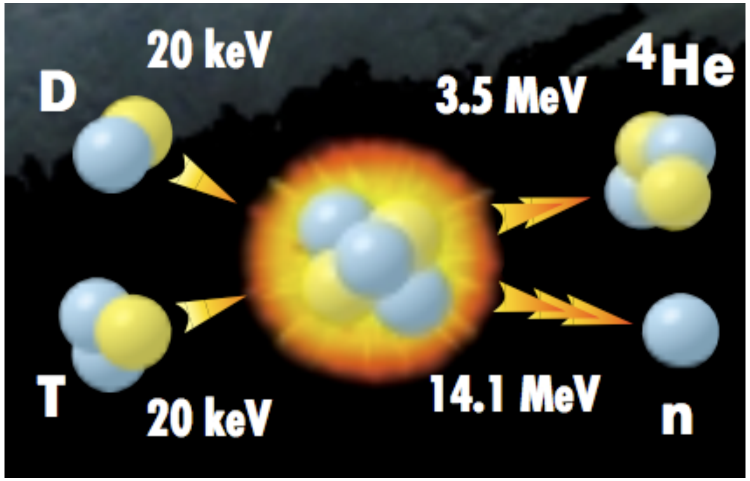
$$n + {}^{6}Li \rightarrow {}^{4}He + T$$

$$n + {}^{7}Li \rightarrow {}^{4}He + T + n$$

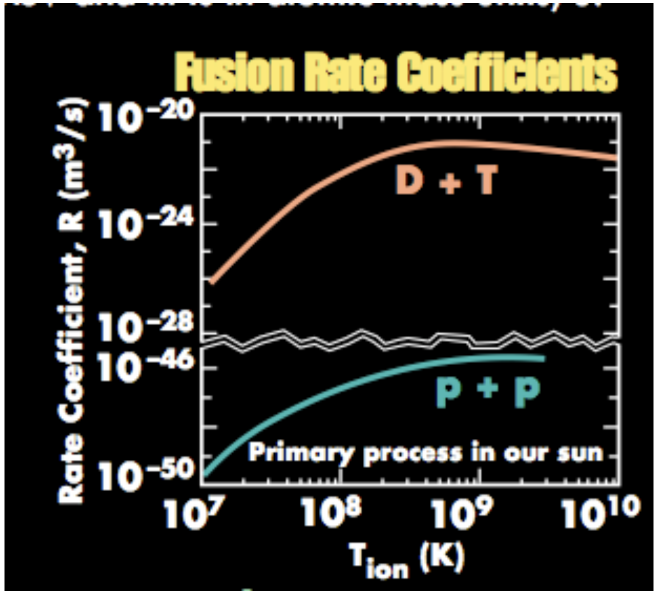
$$D + Li \rightarrow {}^{4}He + 100 \times 10^{6}\ \mathrm{kWh/\ kg}$$

# Fusion reactions : sun vs. earth

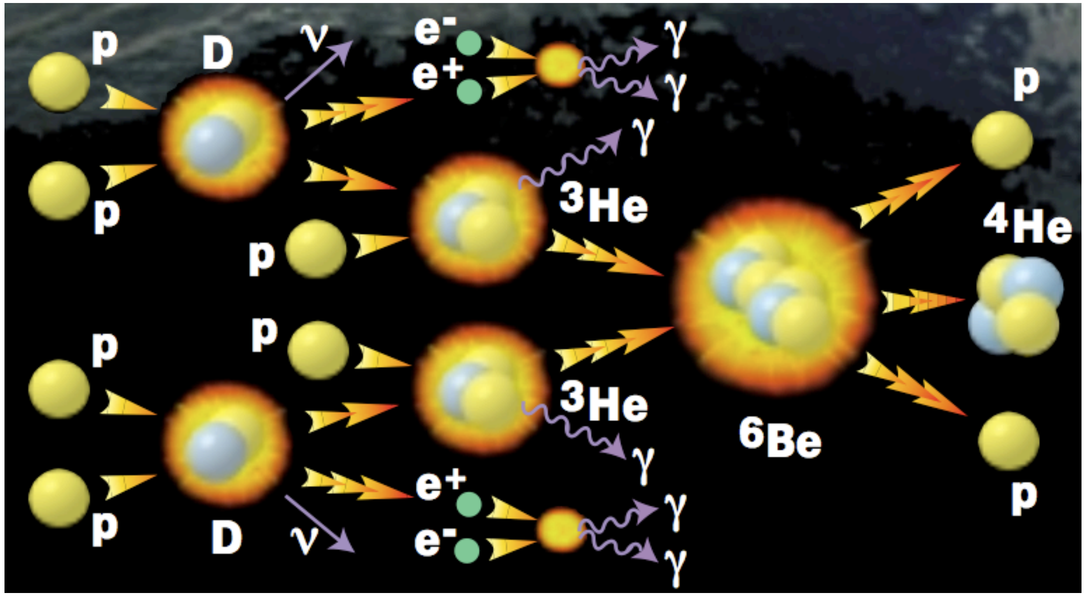
### On earth (D-T)




D-T $10^{25}$ times higher reaction rate




### In the sun (p-p)

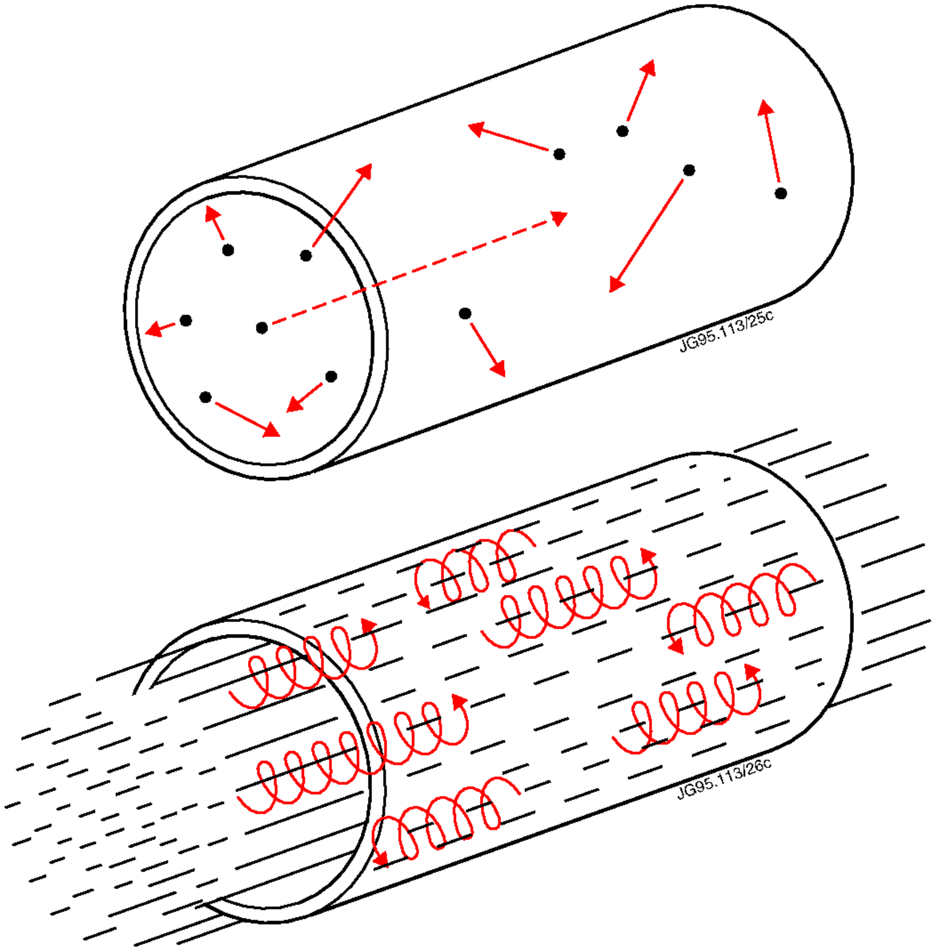


# Advantages of fusion

- Ash is $^4He$
  - — no radioactivity
  - — chemically inert : no ozone depletion, no acid rain,...
  - — no greenhouse effect
  - ⇒ Excellent environmental compatibility
- Does not imply long term storage of radioactive waste
  - — part of fuel is active (tritium), but consumed in reaction
  - — choice of structural materials to reduce long lived activity
  - ⇒ Offers prospect to recycle radioactive waste in 1-2 generations
- Inherently safe
  - — malfunction of control system does not lead to runaway
  - ⇒ Tchernobyl like accident EXCLUDED
- Inexhaustible
  - — fuel consumption is minimal, reaction releases lots of energy
  - ⇒ Energy source for thousands/millions of years
- Energy independence
  - — no geographical dependence for fuel
  - ⇒ Avoid geopolitical difficulties

# Principle of magnetic fusion

## Charged particles 'stick' to magnetic field lines (Lorentz force)



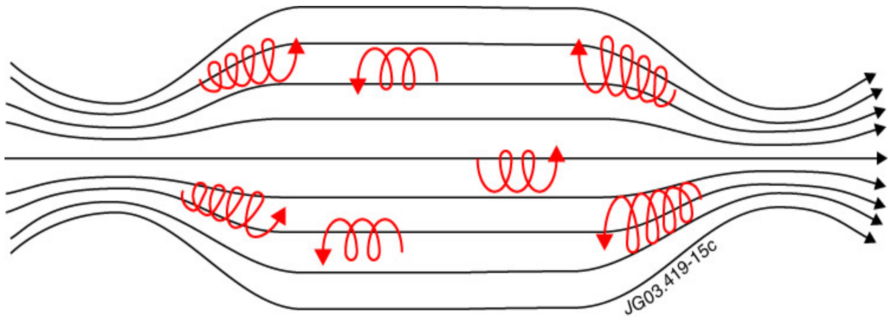

No magnetic field

With magnetic field

# Principle of magnetic fusion

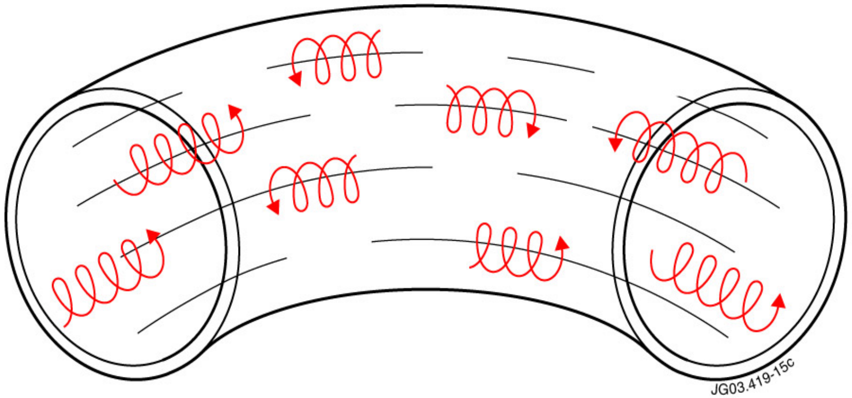
**Particles follow magnetic fields**
**how to limit losses at the end of cylinder?**

**Two possible solutions**




- ‘close' magnetic field at ends

  BUT : too high losses at ends



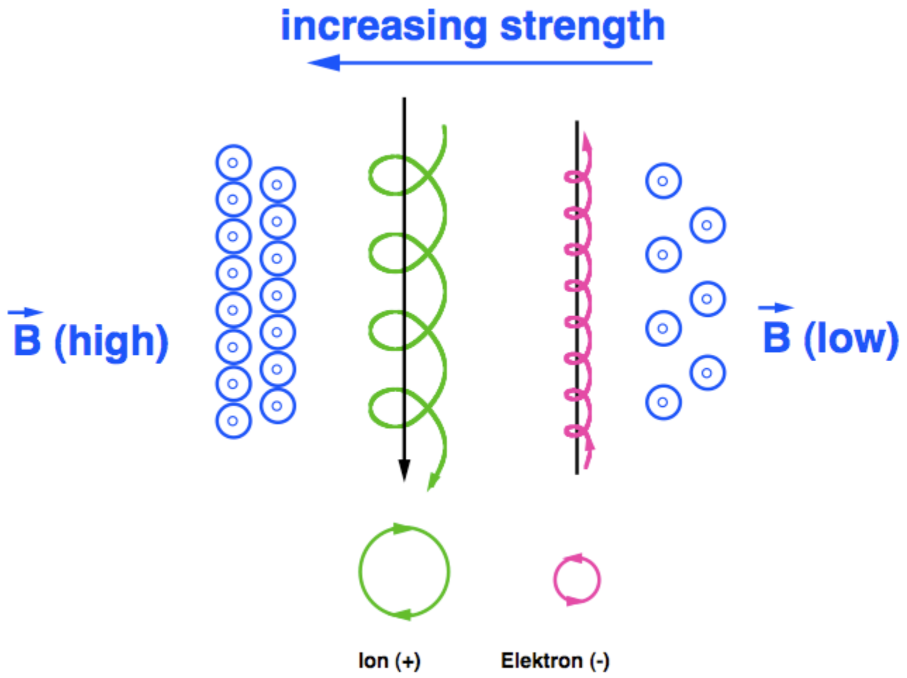

- 'close' magnetic fields on themselves

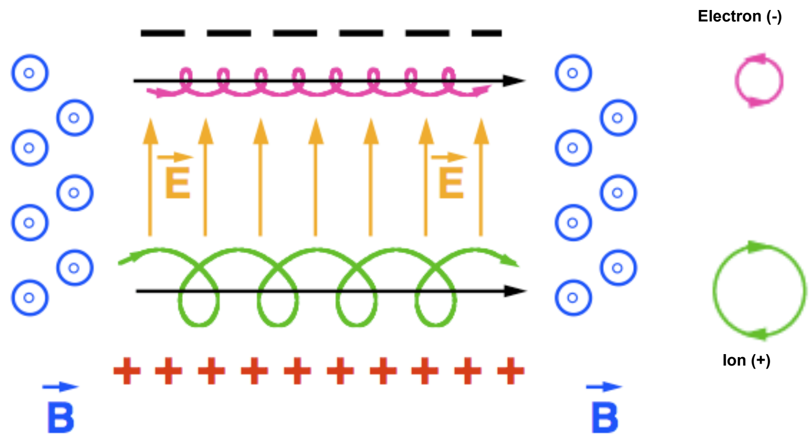
  ⇒ toroidal configuration

# Pure Toroidal field : Charge Separation !

**Pure toroidal magnetic field**
**Charges Separate → Electric Field**

**Magnetic field + Electric Field**
**ALL particles move outward !**



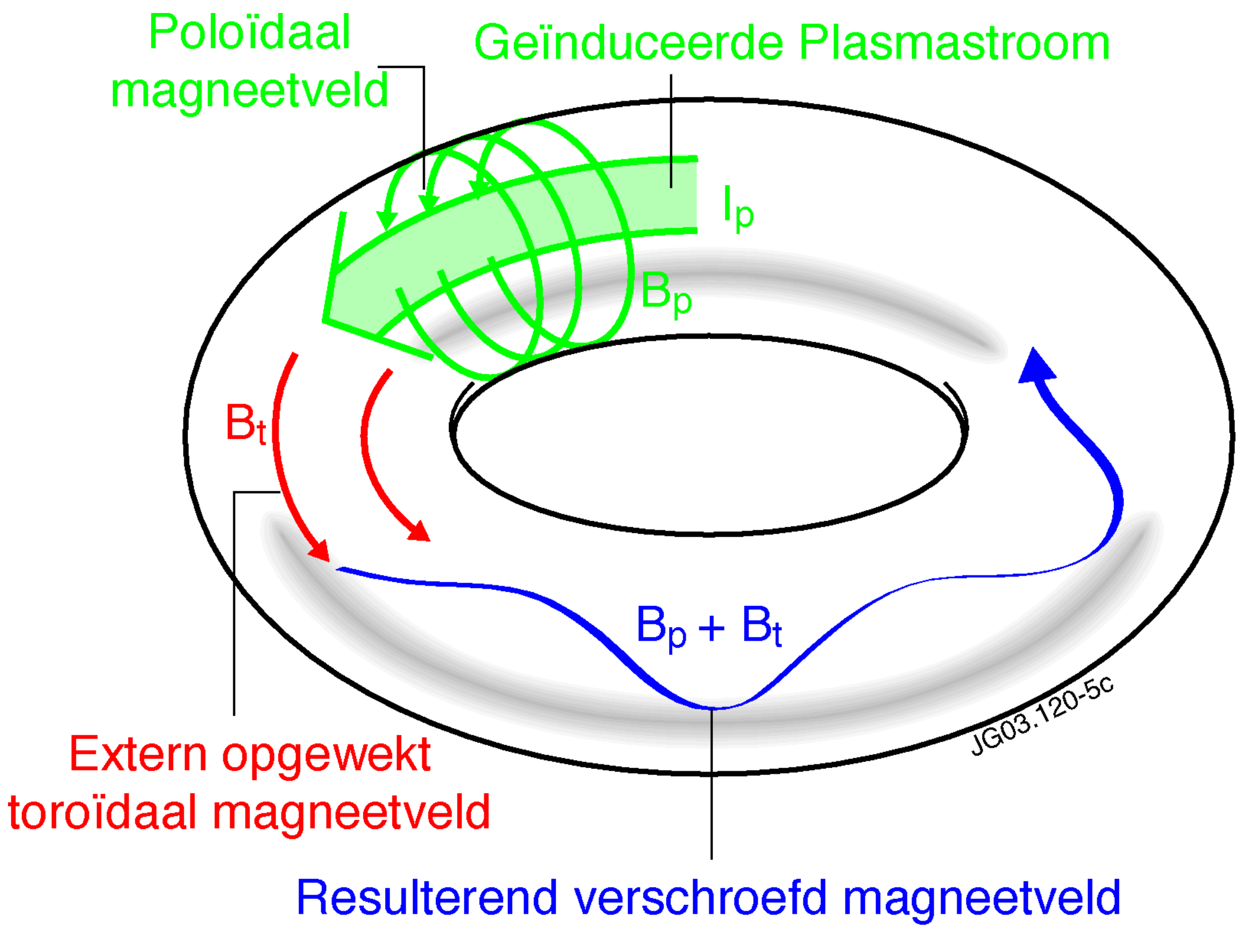

**Fundamental Reason:**
**Gyroradius varies with magnetic field and particle speed**

$$\rho_L = \frac{mv_\perp}{qB}$$

# Helical Magnetic Field : option 1

## Tokamak

### Large current induced in plasma (~100kA - 10MA)



# Principle of the tokamak

- **Tokamak**, from the Russian words:

  **to**roidalnaya **ka**mera, s **ma**gnitnami **k**atushkami

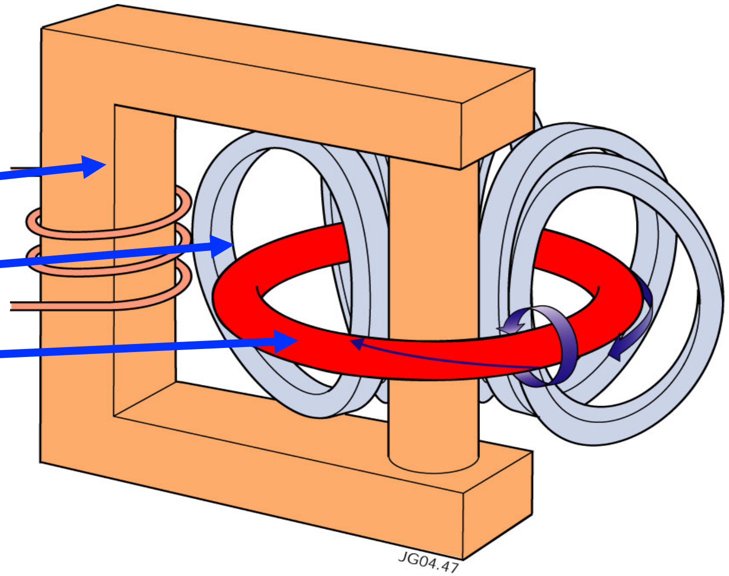
  meaning "**toroidal chamber**" with "**magnetic coils**"


- Invented by : **Andrei Sacharov** and **Igor Tamm**

  (both Noble Prize Winners)

  at the Kurchatov Institute in Moscow in 1950

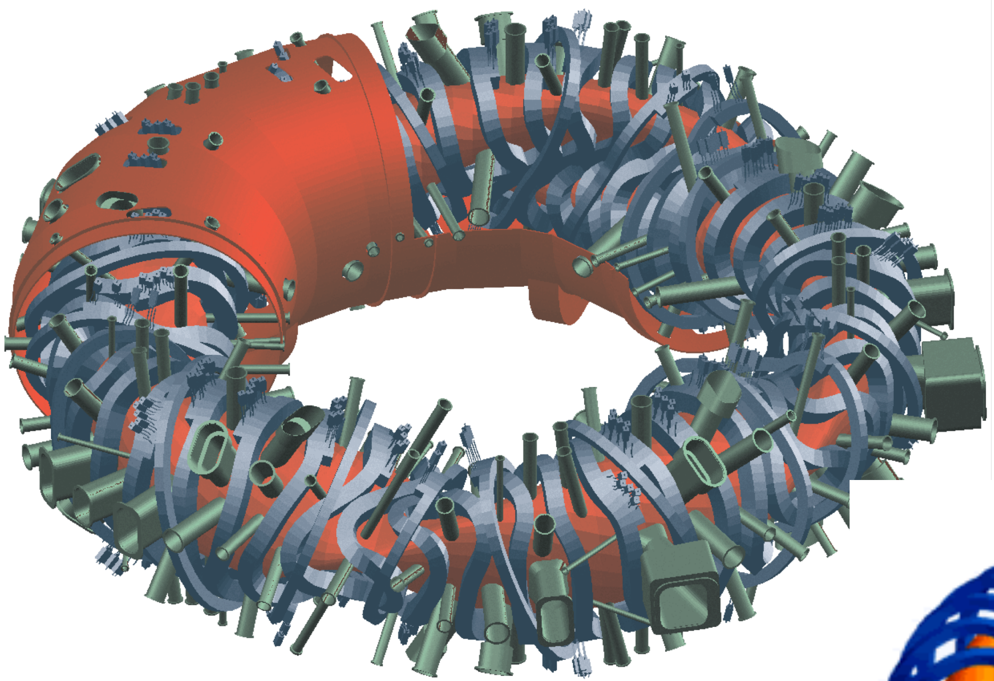
- Essentially a tokamak consists of :
  - — large transformer
  - — coils for magnetic fields
  - — plasma ring with large plasma current

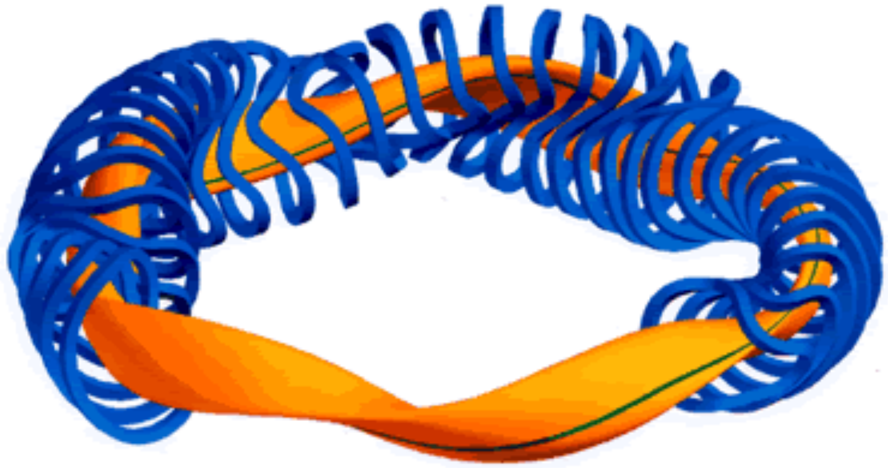


# Helical Magnetic field : option 2

## Stellarator

**Very ingenious coils generate directly a helical field**



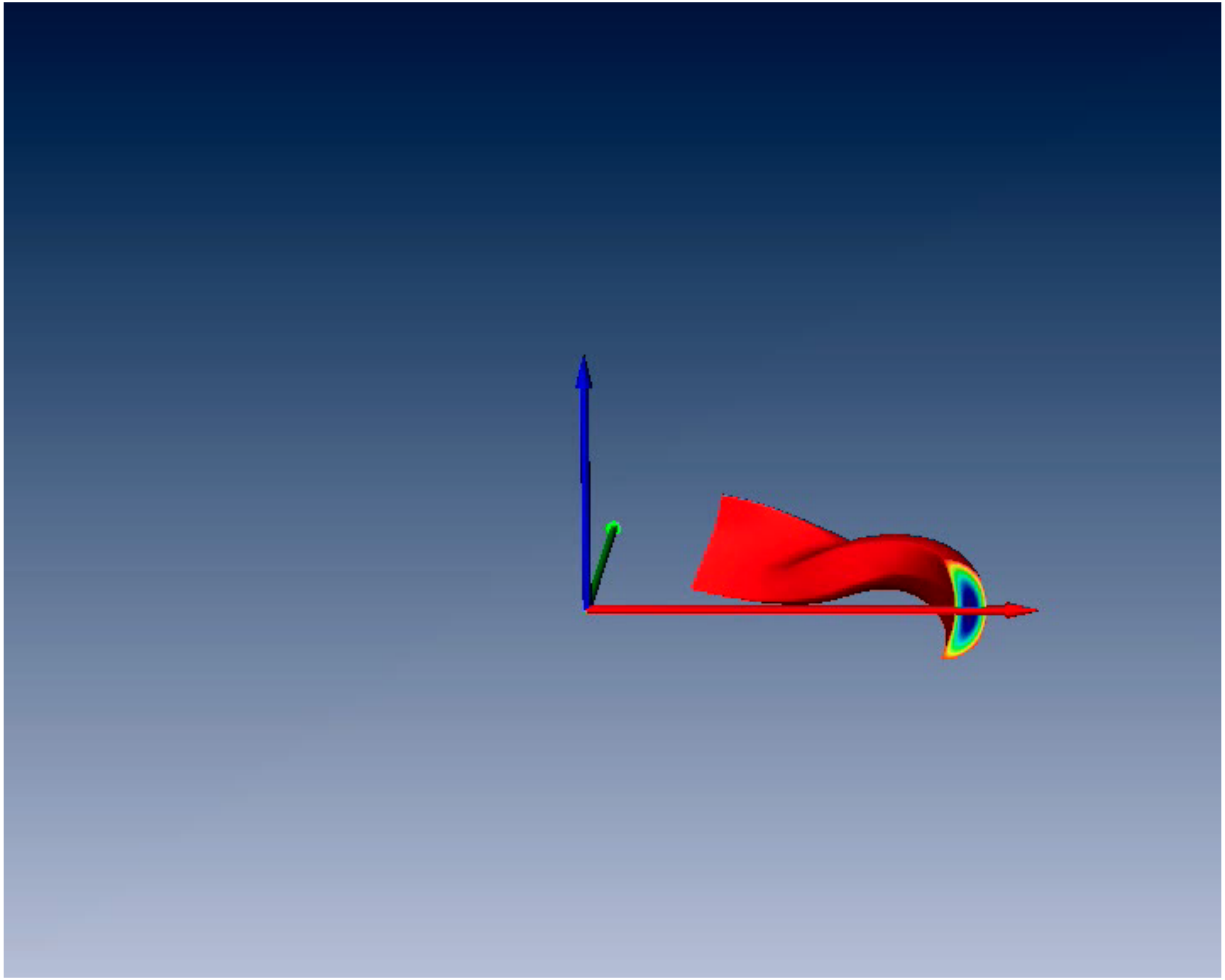


**No plasma current**

⇒ no transformer

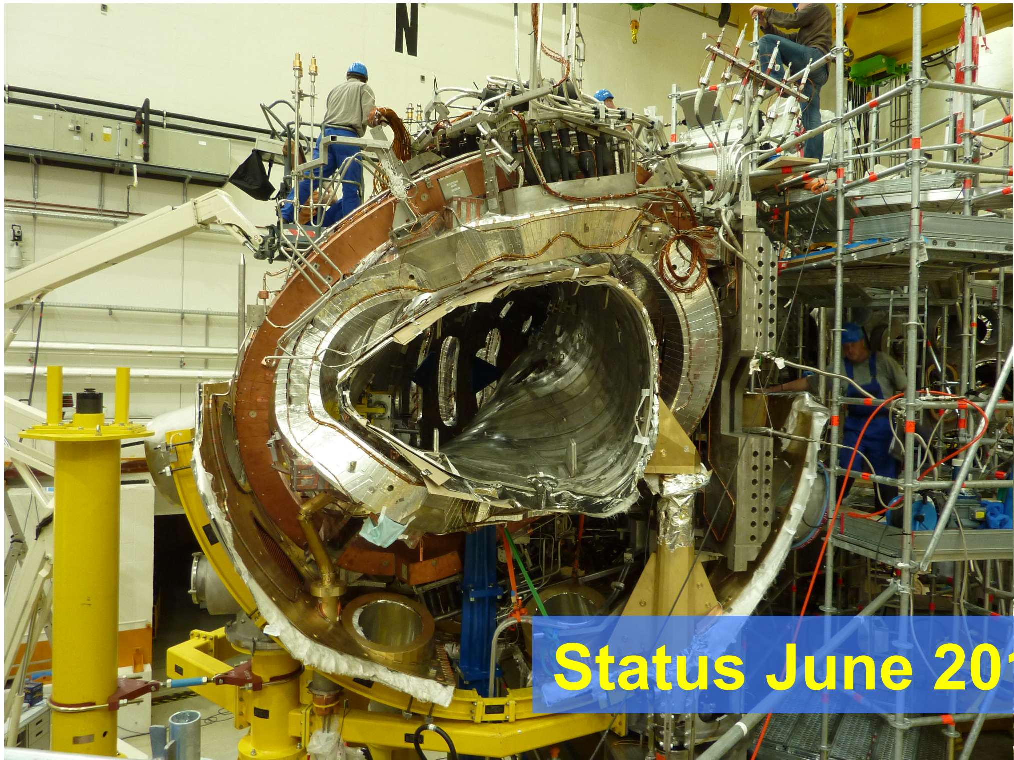
⇒ continuous operation

# Magnetic surfaces in W7X Stellarator



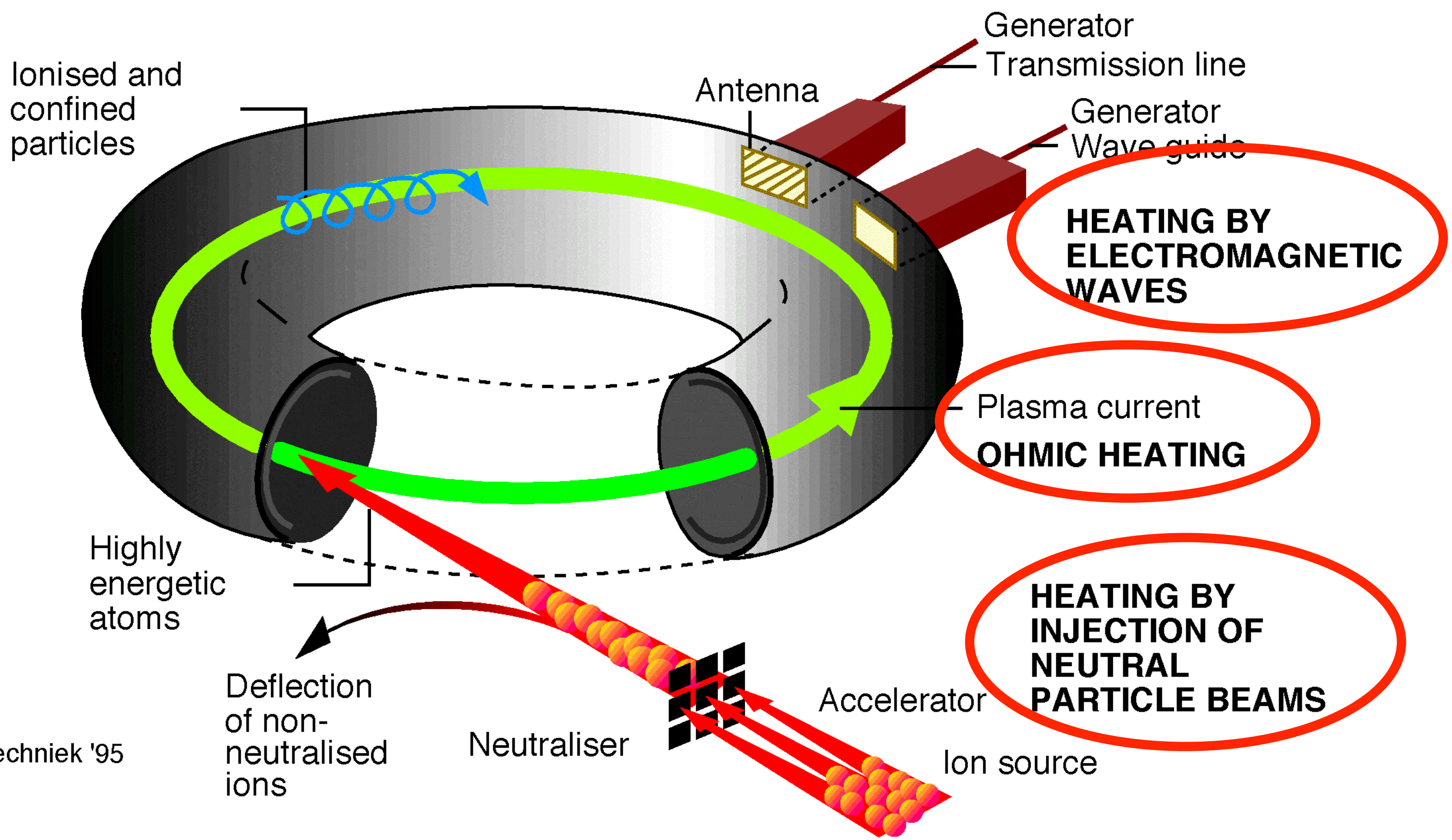
# Status of W7X : largest Stellarator worldwide

**First operation expected in 2015**



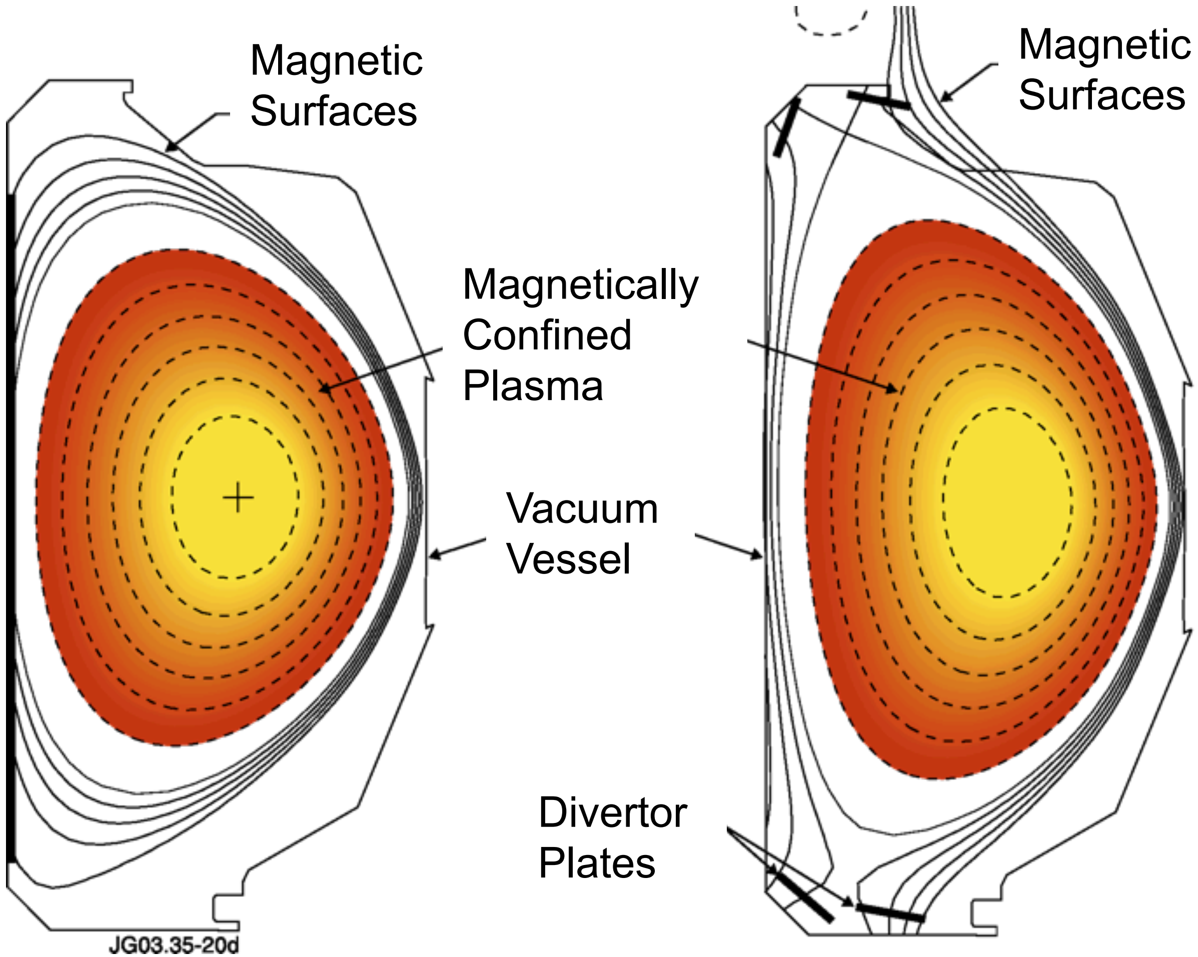

# How to create ultra-high temperatures ?

## IN A FUTURE FUSION REACTOR : HEATING BY ALFA PARTICLES



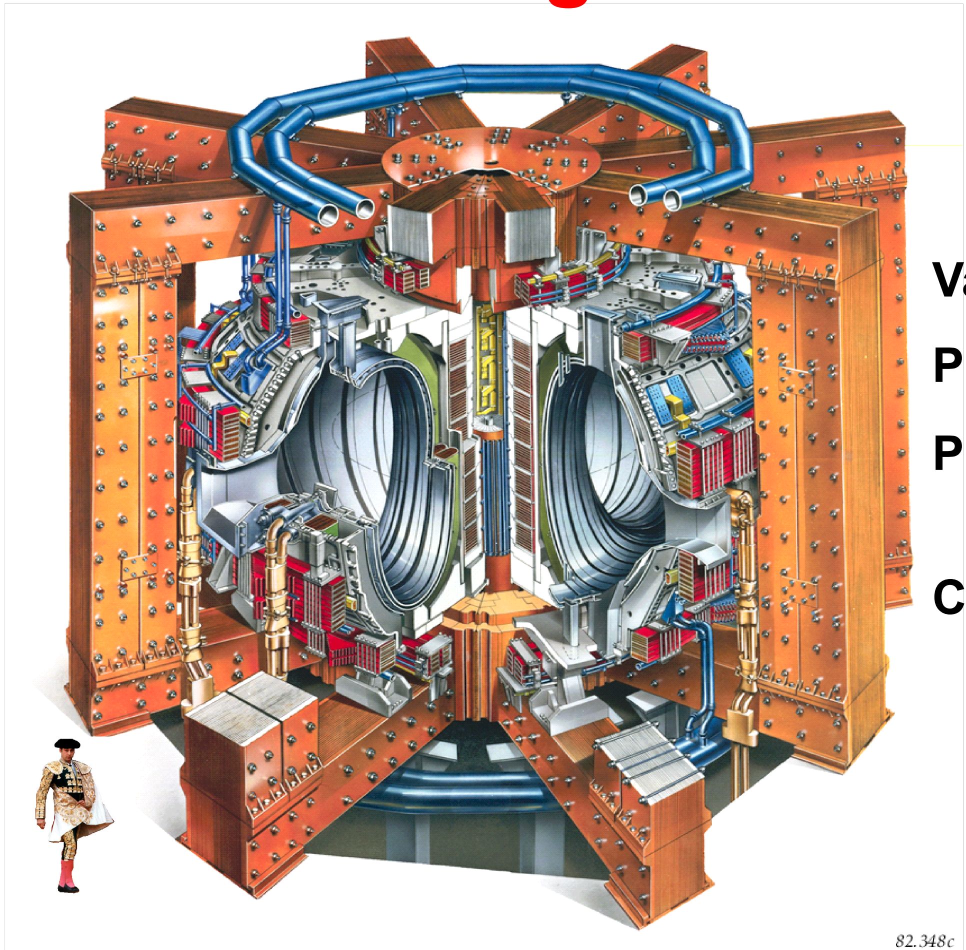
# Two tokamak plasma configurations

## Limiter  Divertor



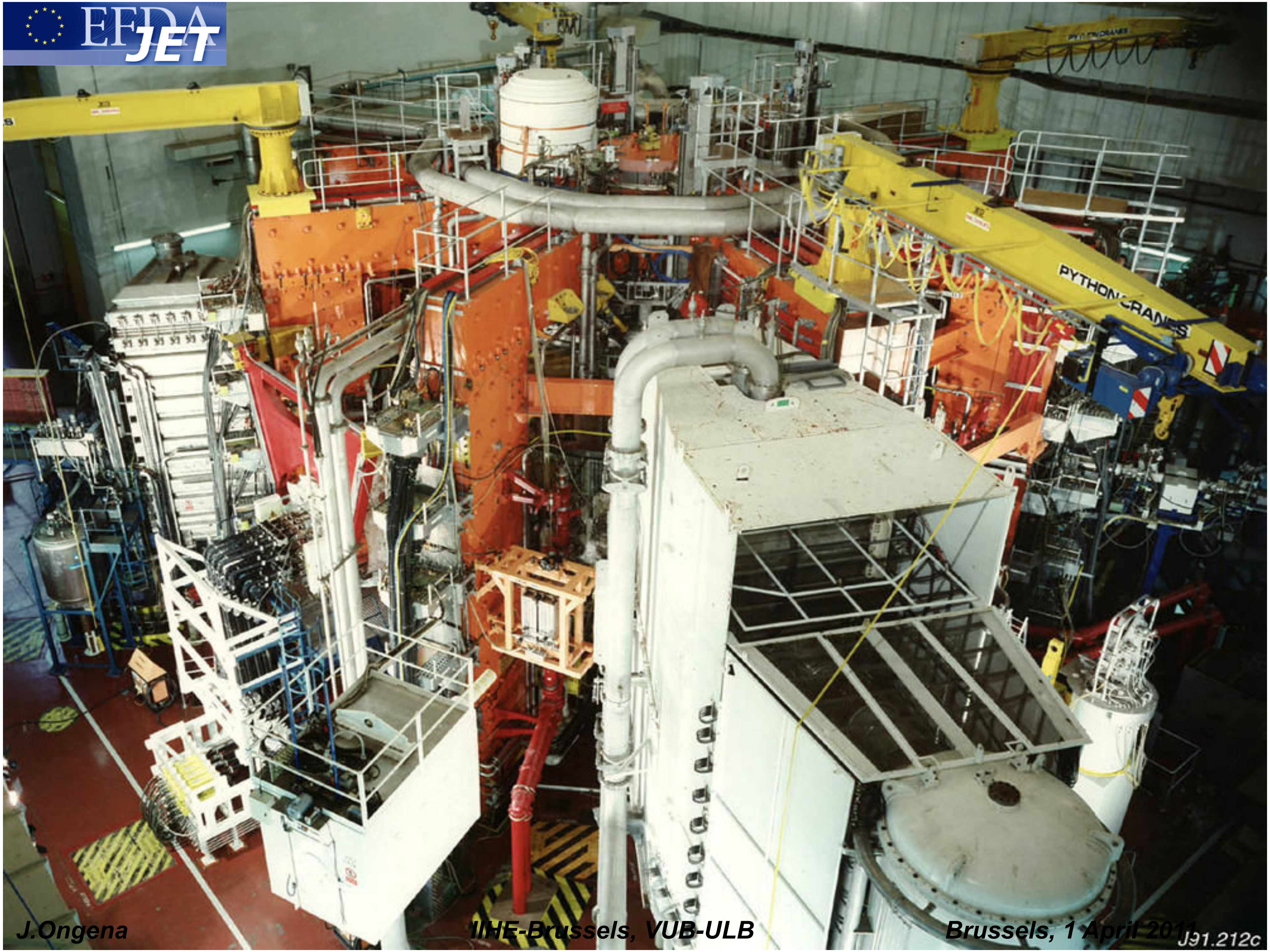
# Joint European Torus (JET)
# The largest tokamak in the world
### (in Culham, about 10km from Oxford)

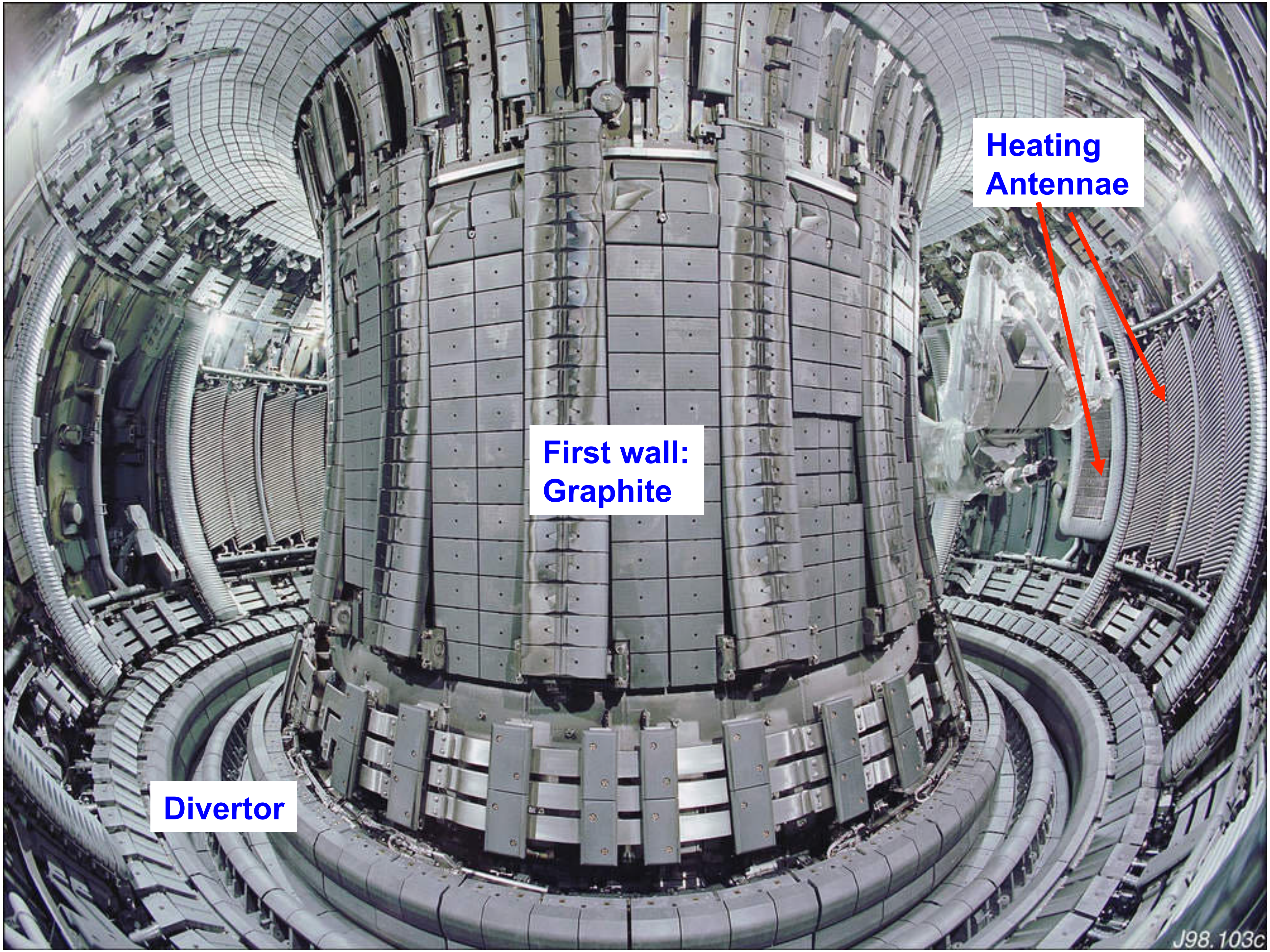
# Joint European Torus (JET)
# Common European Facility (Oxfordshire, UK)
# Largest tokamak worldwide




| | |
|---|---|
| **Vacuum vessel** | **3.96m high x 2.4m wide** |
| **Plasma volume** | **80 m$^3$ - 100 m$^3$** |
| **Plasma current** | **up to 5 MA**<br>**in present configurations** |

**Confining magnetic field up to 4 Tesla**

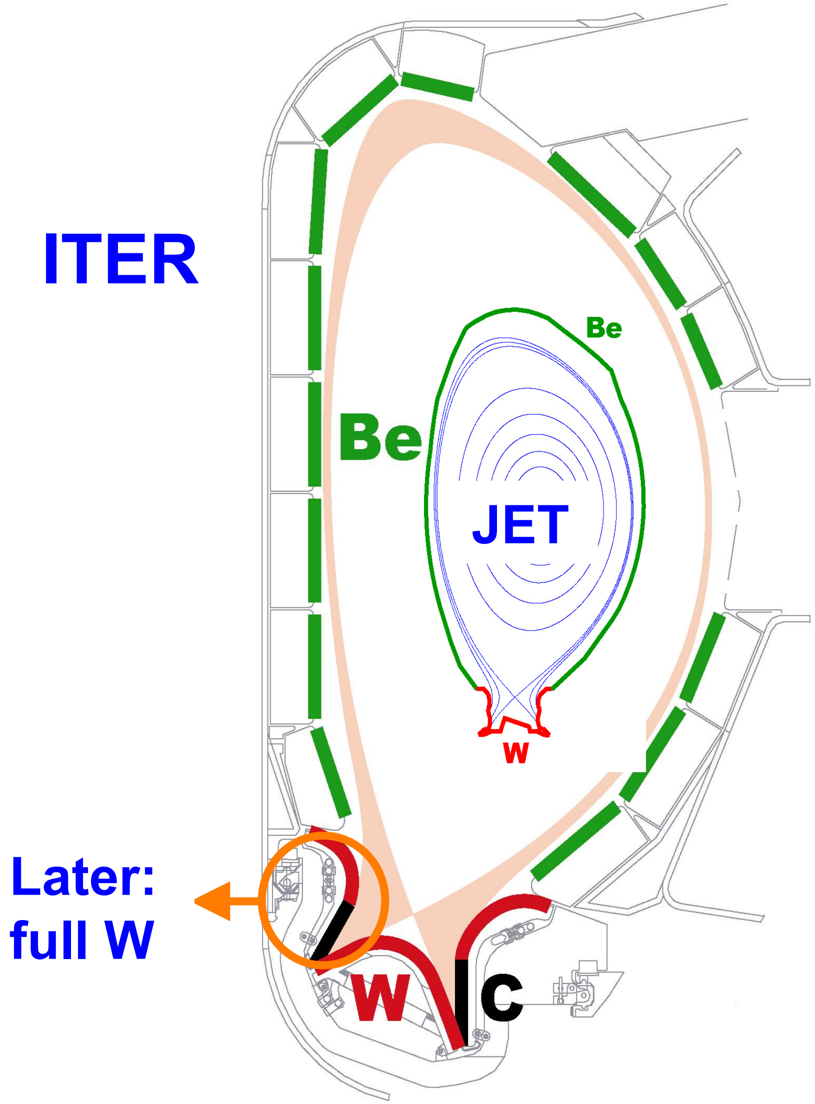

PYTHON CRANES
J91.212c

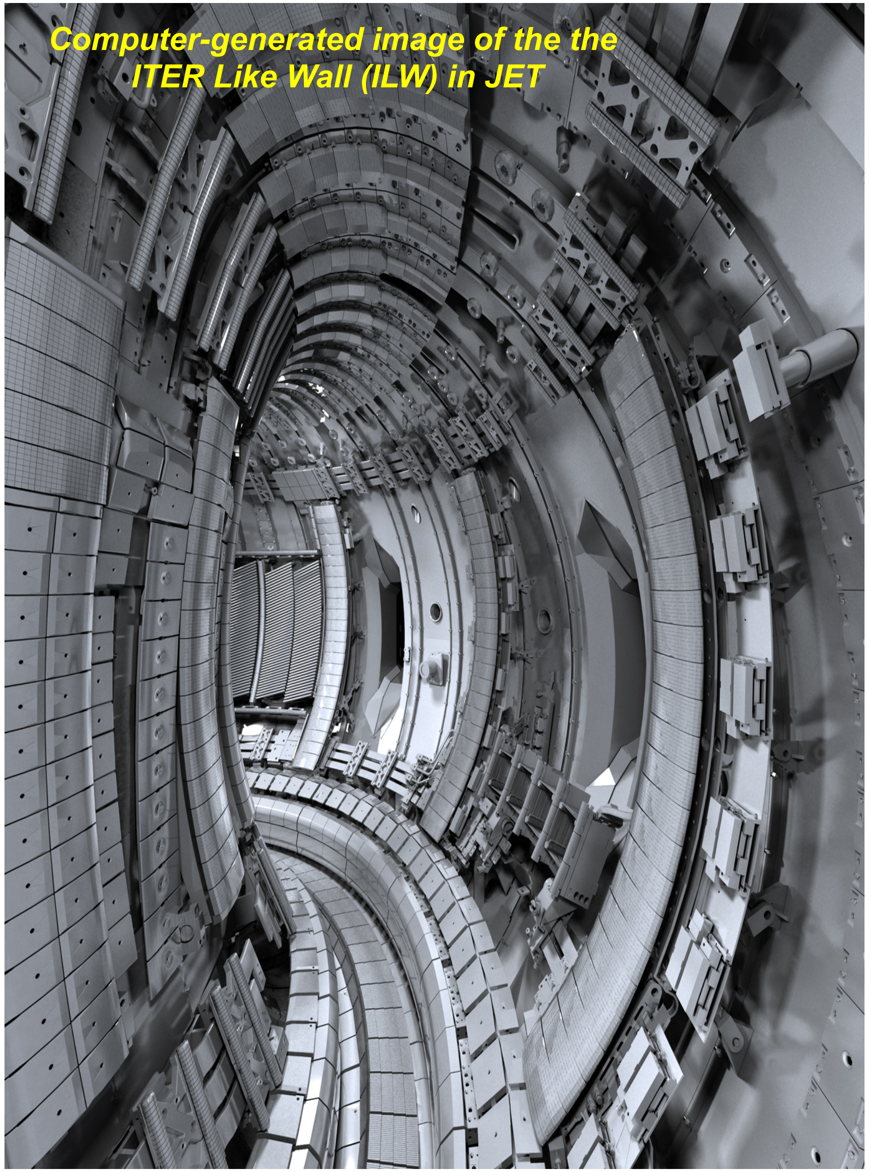


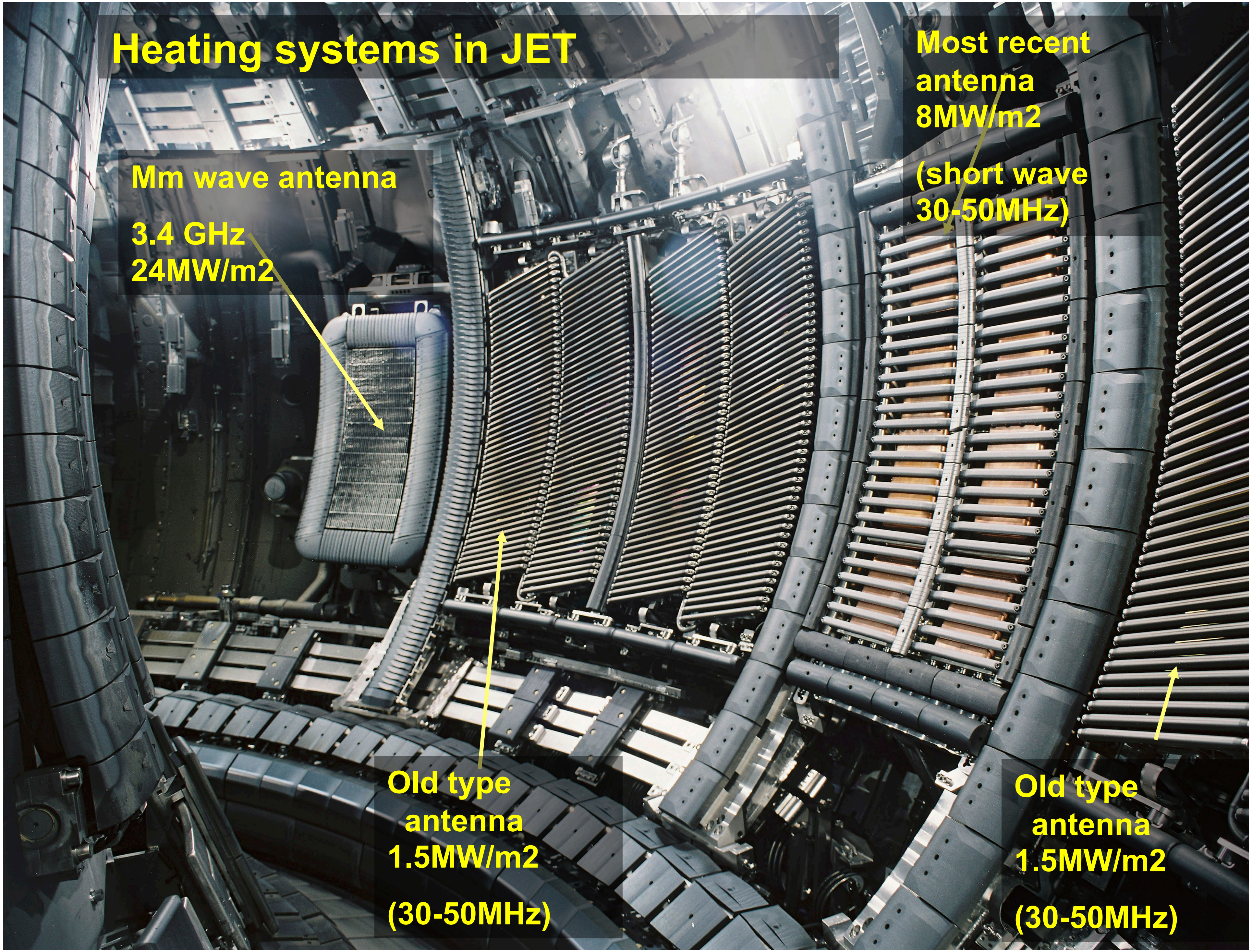
Heating Antennae
First wall: Graphite
Divertor
J98.103c

# Soon it will look like this (mid 2011) !

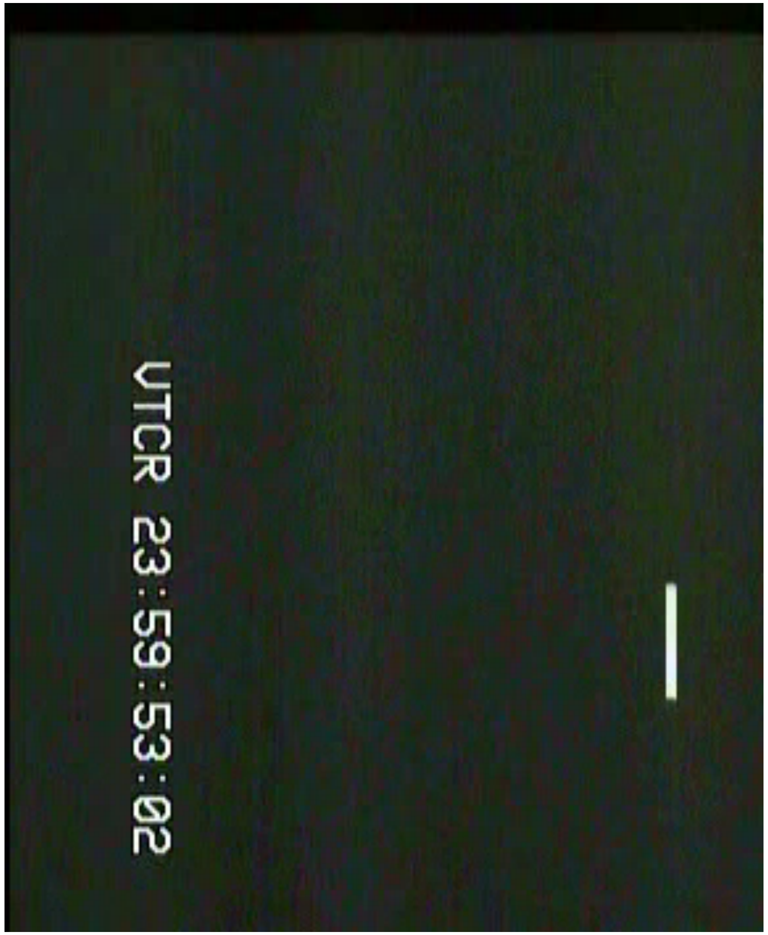
## Be + W first wall

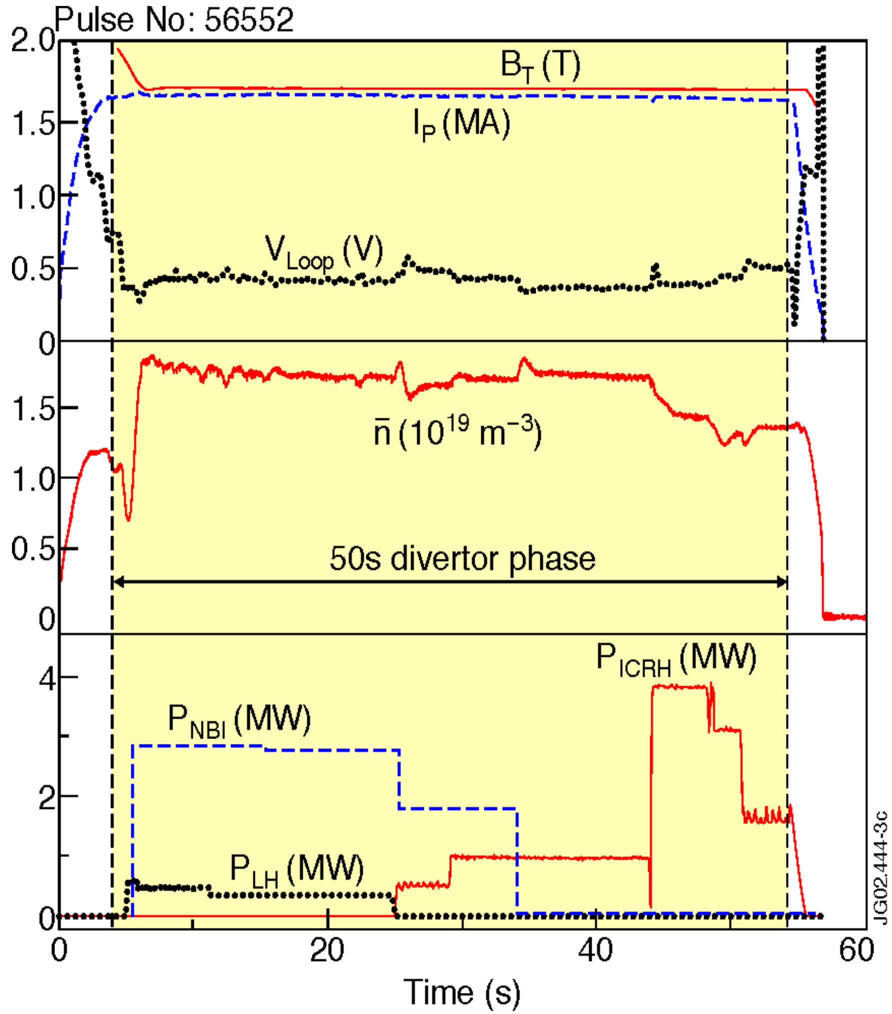



Heating systems in JET
Mm wave antenna
3.4 GHz
24MW/m2
Most recent antenna
8MW/m2
(short wave
30-50MHz)
Old type antenna
1.5MW/m2
(30-50MHz)
Old type antenna
1.5MW/m2
(30-50MHz)

# 1 min long JET Plasmas in ITER configuration




Recent : Tore Supra (Frankrijk): 6min30s, LHD (Japan): 30min

# Plasma Energy W and Energy confinement time $\tau_E$

$$\mathbf{W} = 1.5 \int_V k\,[n_e(r)\,T_e(r) + n_i(r)\,T_i(r)]\,dV$$

$$\frac{dW}{dt} = P - \frac{W}{\tau_E} \qquad \text{If } P = 0 \Rightarrow W(t) = \frac{W}{P}\, e^{-t/\tau_E}$$

**$\tau_E$ measures how fast the plasma looses its energy**

**$\tau_E$ is a measure for the thermal insulation of the plasma**

Experimentally :

Under stationary conditions (dW/dt=0) : $\tau_E = \frac{W}{P}$

# Plasma Beta

$$\beta = \frac{W}{B^2/2\mu_0} = \frac{\text{Plasma pressure}}{\text{Magnetic pressure}} \quad (\beta \sim \text{a few \%})$$

$$\beta_N = \frac{\beta}{I_p/(aB_t)}$$

'Normalised beta' (ITER $\beta_N \sim 1.8\text{-}4$)

$\beta$ determines the fusion power output of a power reactor as

$$P_f = 5P_\alpha \propto N^2T^2\,\mathrm{Vol} \propto \beta^2 B_t^4\,\mathrm{Vol}$$

An important aim of fusion research is to maximise $\beta$

BUT: if $\beta$ too high $\rightarrow$ MHD instabilities

# Conditions to sustain reaction
# Lawson Criterion

For the fusion reaction to propagate,

conditions must be maintained

**Heating power must be large enough to compensate for the losses**

**$n^2 <\sigma(T) v>$ + external power**

**radiation losses $n^2 T^{1/2}$**

**convection and conduction $n T / \tau_E$**

---

**n (density) x $\tau_E$ (confinement time) > function of T (Temperature)**

**Lawson Criterion**

# Power Amplification Factor Q

$$Q = \frac{P_{fusion}}{P_{external\ heating}}$$

**Breakeven Q=1**

when Pfusion = Pexternal heating

**Ignition Q = ∞**

when Pexternal heating = 0: no external heating needed
Selfsustained fusion reaction

Note:

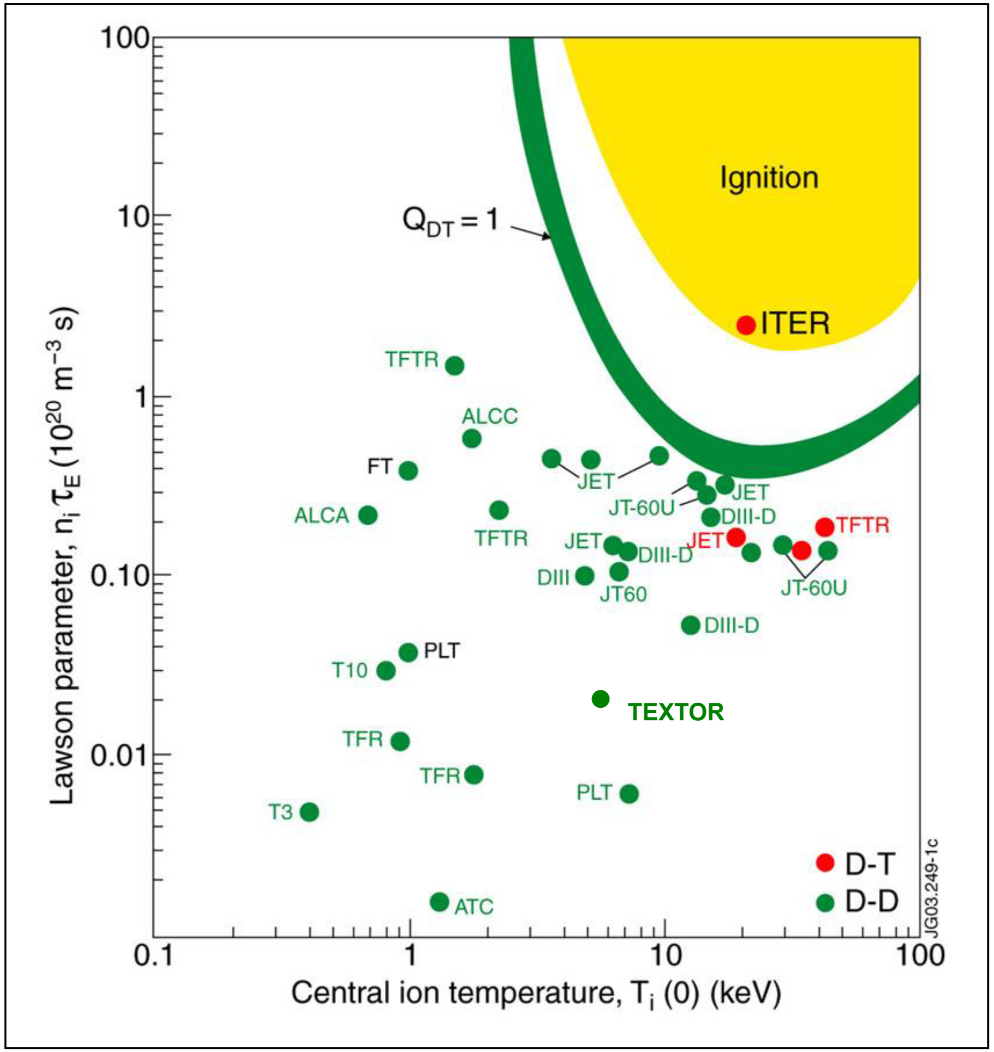
Q relates to the **balance between fusion and external heating power only**

It is **not** representative for the balance between total power consumption (magnetic fields, additional systems) and fusion power output

# Results obtained close to break-even

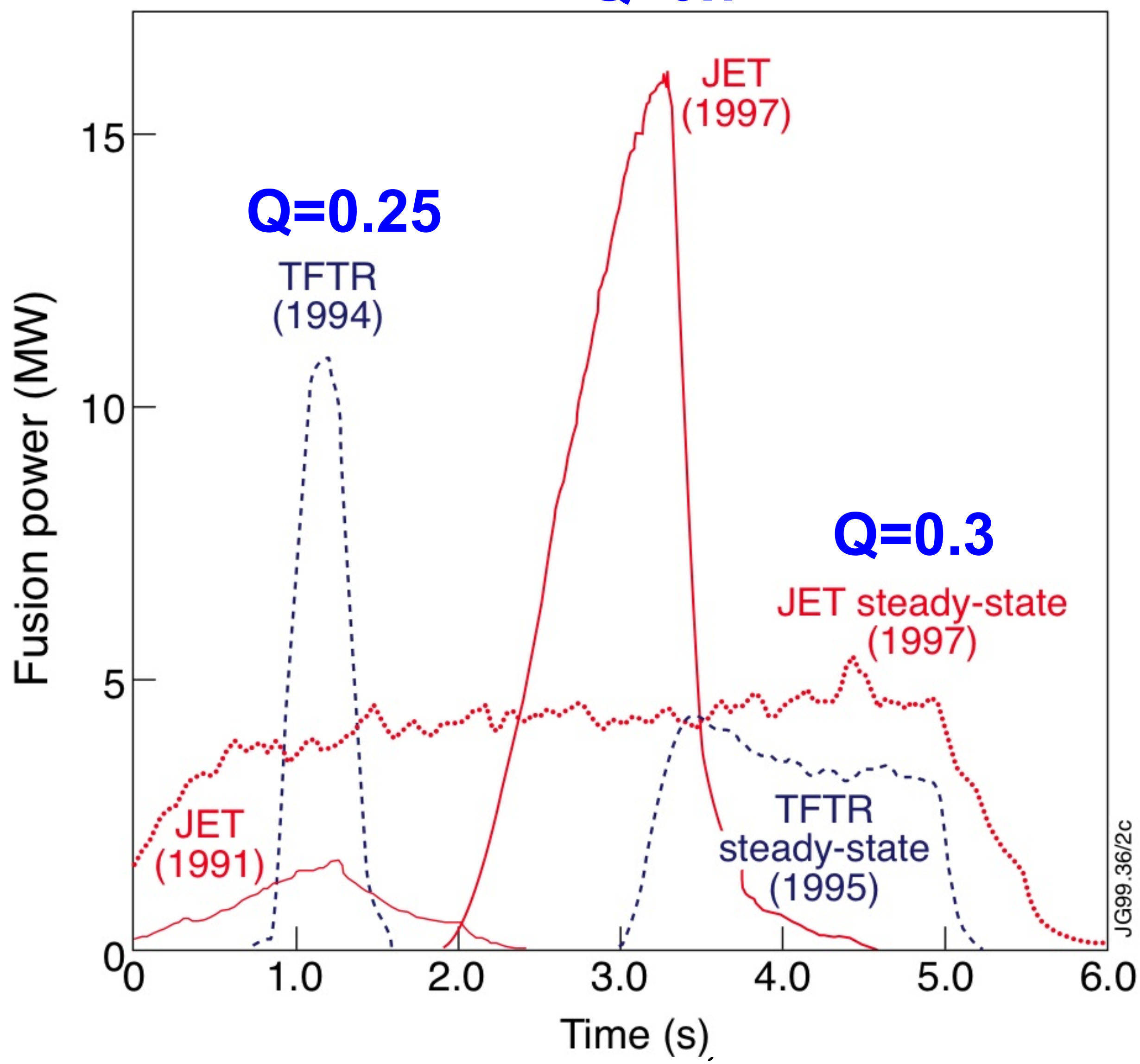
**Present machines are close to produce fusion energy comparable with the energy required to sustain the plasma (breakeven : Q=1)**

**Next step devices (ITER) are expected to produce significantly more fusion energy than the energy required to sustain the plasma (close to Ignition Q=∞)**



# Record Fusion Performance in JET (16MW , obtained in 1997)

Q=0.7




Results from D-T plasmas

*J.Ongena* *Brussels, 1 April 2011*

EFDA JET

# iter

china eu india japan korea russia usa

# ITER: A unique international project

**More than half of the world population is represented,**
**Important participation of new economies !**

iter

china eu india japan korea russia usa

## 500MW fusion power
## Construction close to Aix-en-Provence

# Why do we need ITER?

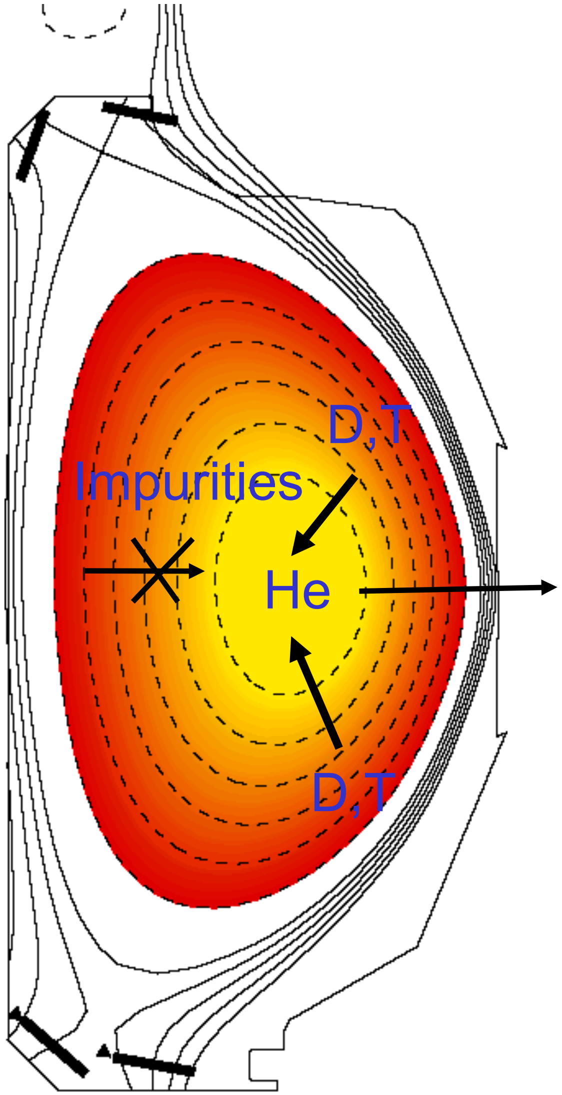
Essentially we have learnt 'how to start the fusion fire'

- Configuration where fusion reactions are feasible : OK
- Reaching the necessary high temperatures : OK
- Confine hot plasmas for seconds/minutes : OK
- D-T fusion plasmas with multimegawatt output : OK

Main difference between ITER and current machines
What do we need to learn ? 'how to maintain the fusion fire'

**Much longer plasma duration**
**Much higher fusion power**
**A steady source of He in the centre**
**A steady flow of high energy neutrons**

# How to maintain the fusion fire ?




Physics Questions

• Clean plasma centre :

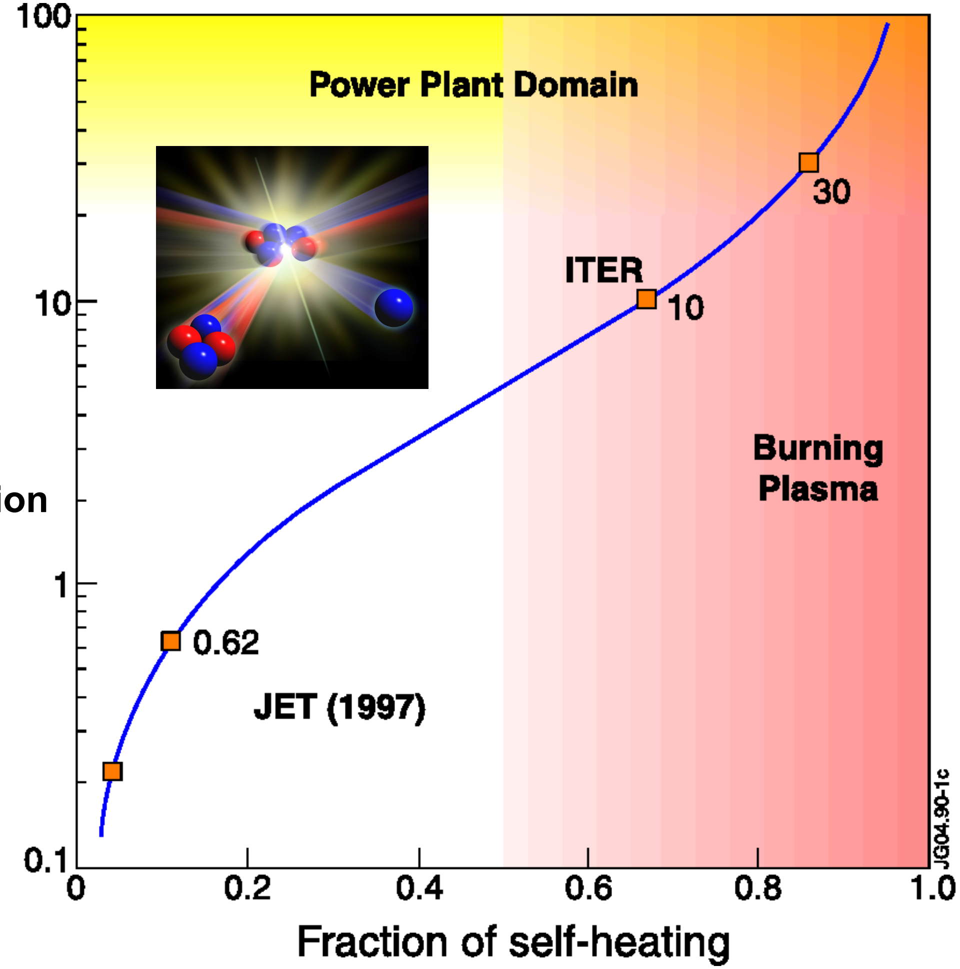
- Remove He sufficiently fast removal
  - Keep impurity level sufficiently low

• Reactive plasma :
- Optimize fuelling (D,T) of plasma centre

• Plasma stability :
- Suppress possible He induced instabilities

Technological Questions
- Optimise first wall and plasma facing components
- Test Tritium breeding from Lithium

# Why do we need ITER ?




Q
Power
Amplification

$f_\alpha$

Fraction of plasma self-heating by fusion born α-particles

$f_\alpha = Q / (Q+5)$

JET (1997) Q ~1 → $f_\alpha$ ~0.15

ITER : Q > 10 → $f_\alpha$ > 2/3

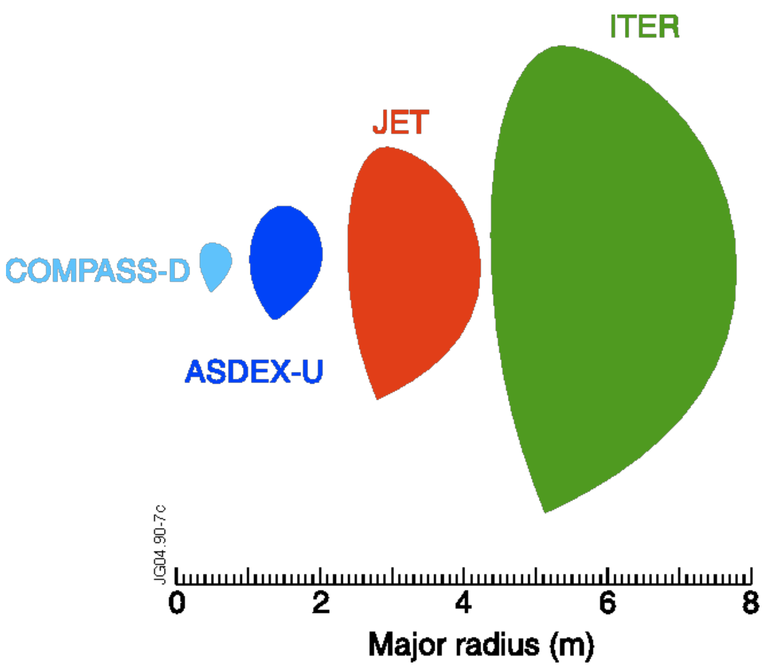
# Necessities for ITER

Very long discharges
— No longer copper coils, but superconducting coils

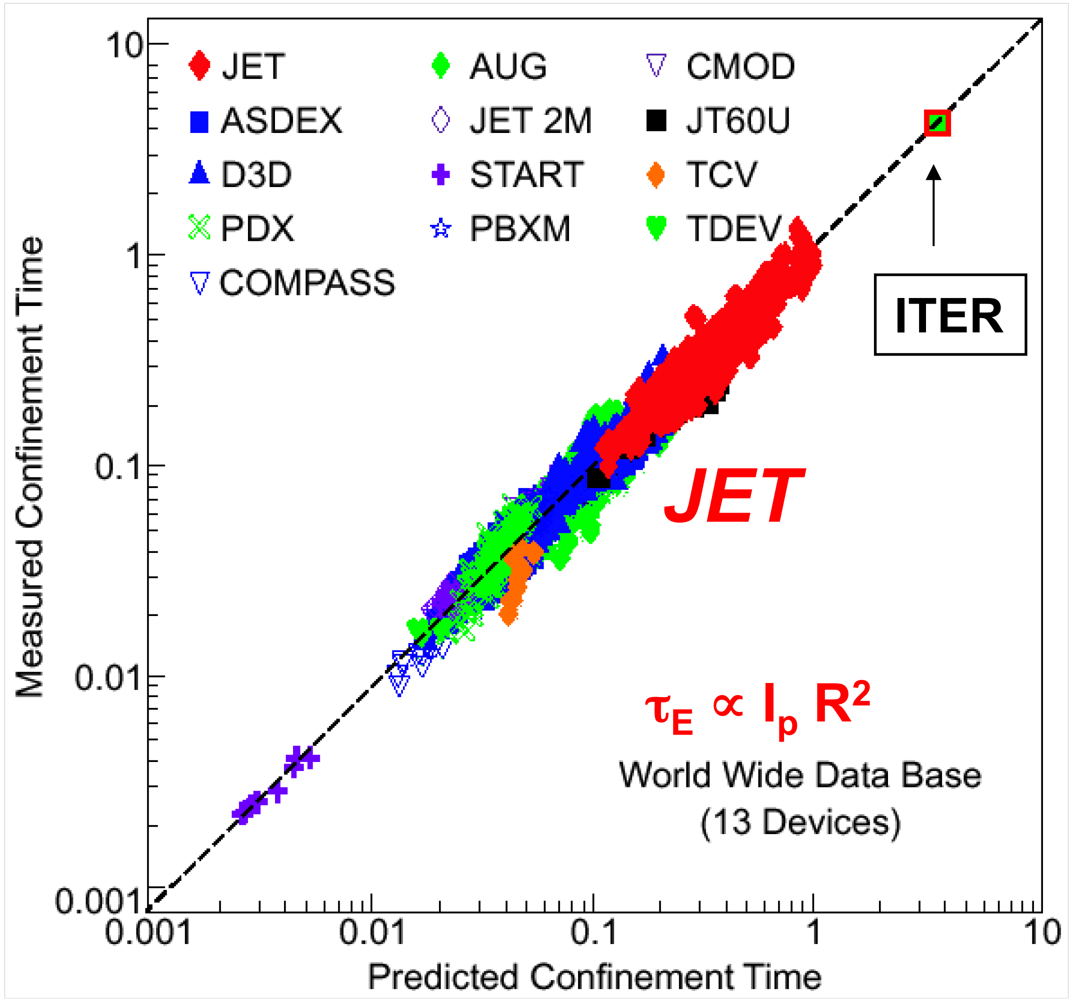
Sufficient heating by fusion alfa particles
— Sufficient number of fusion reactions
needs improved thermal insulation of the plasma
— Therefore : sufficiently large $\tau_E \propto R^2$
— Therefore : sufficiently large device

**Scaling laws show us :**
**ITER size = between 2 and 3 times the size of JET**

# ITER definition (largely based on JET)



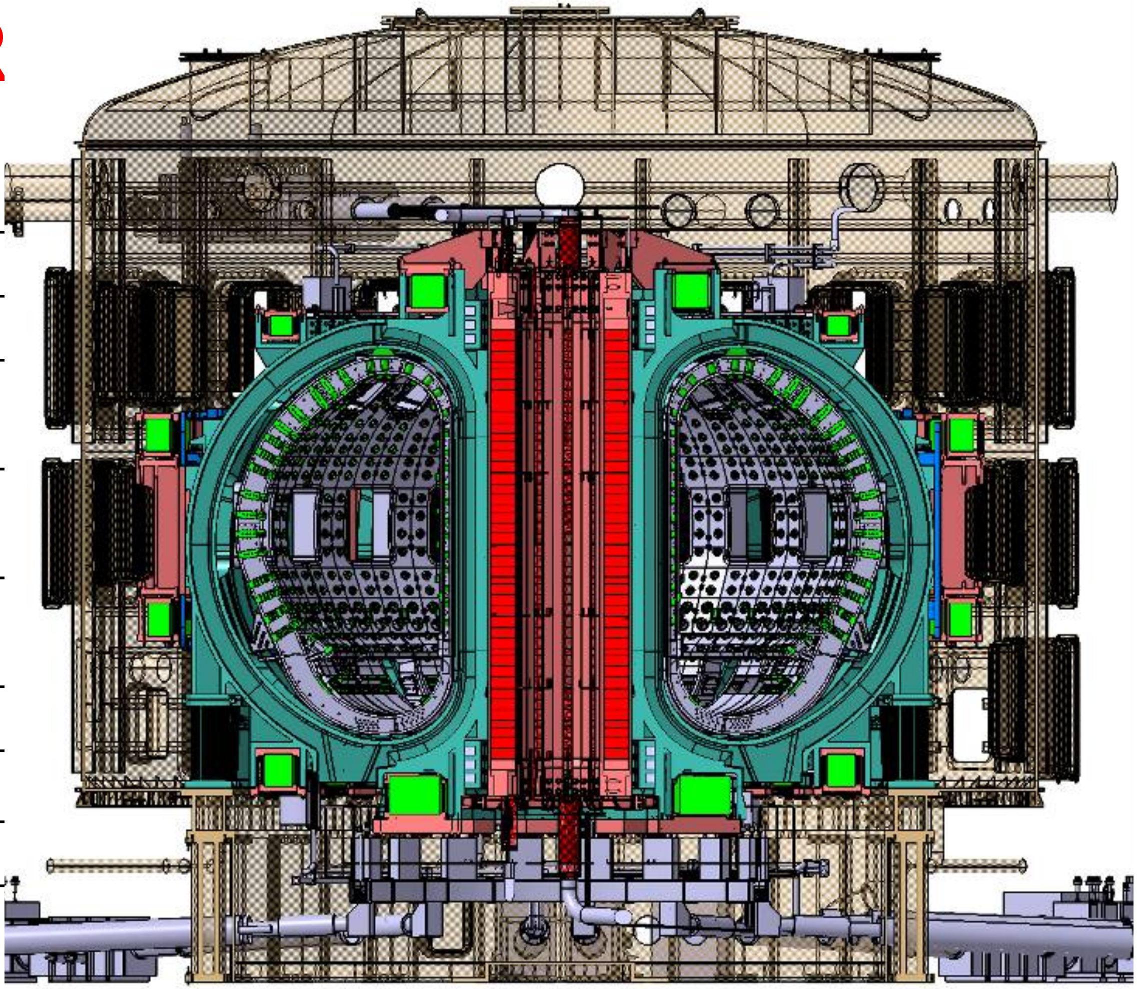

*Cross section of present EU D-shaped tokamaks compared to the ITER project*




**Confinement time $\tau_E = W_{plasma}/P_{input}$**

# 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 | ≥ 0.5 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

# The future for magnetic fusion is being prepared


# ITER – 22 December 2010

# ITER – 26 March 2011

## *Content of the talk*

*I. Why fusion research ?*

*II. How to realise fusion on earth and current status*

*a. Tokamak - Stellarator*

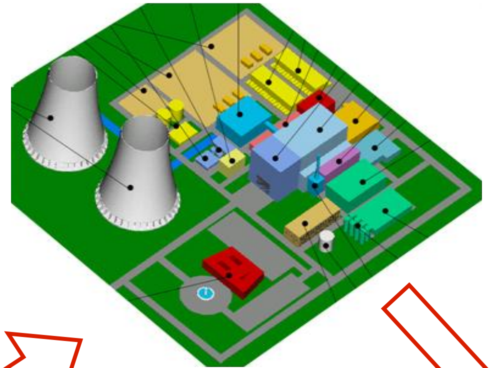
*b. The largest tokamak in the world : JET*

*c. The next step : ITER*

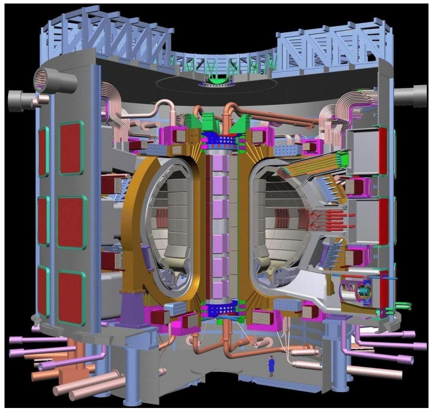
*III. Conclusions*

# EU fusion roadmap

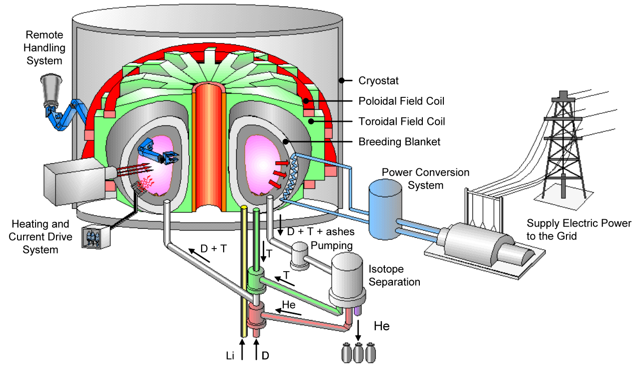
**DEMO objectives**
to bridge the gap between ITER and the first FPP



**DEMO**



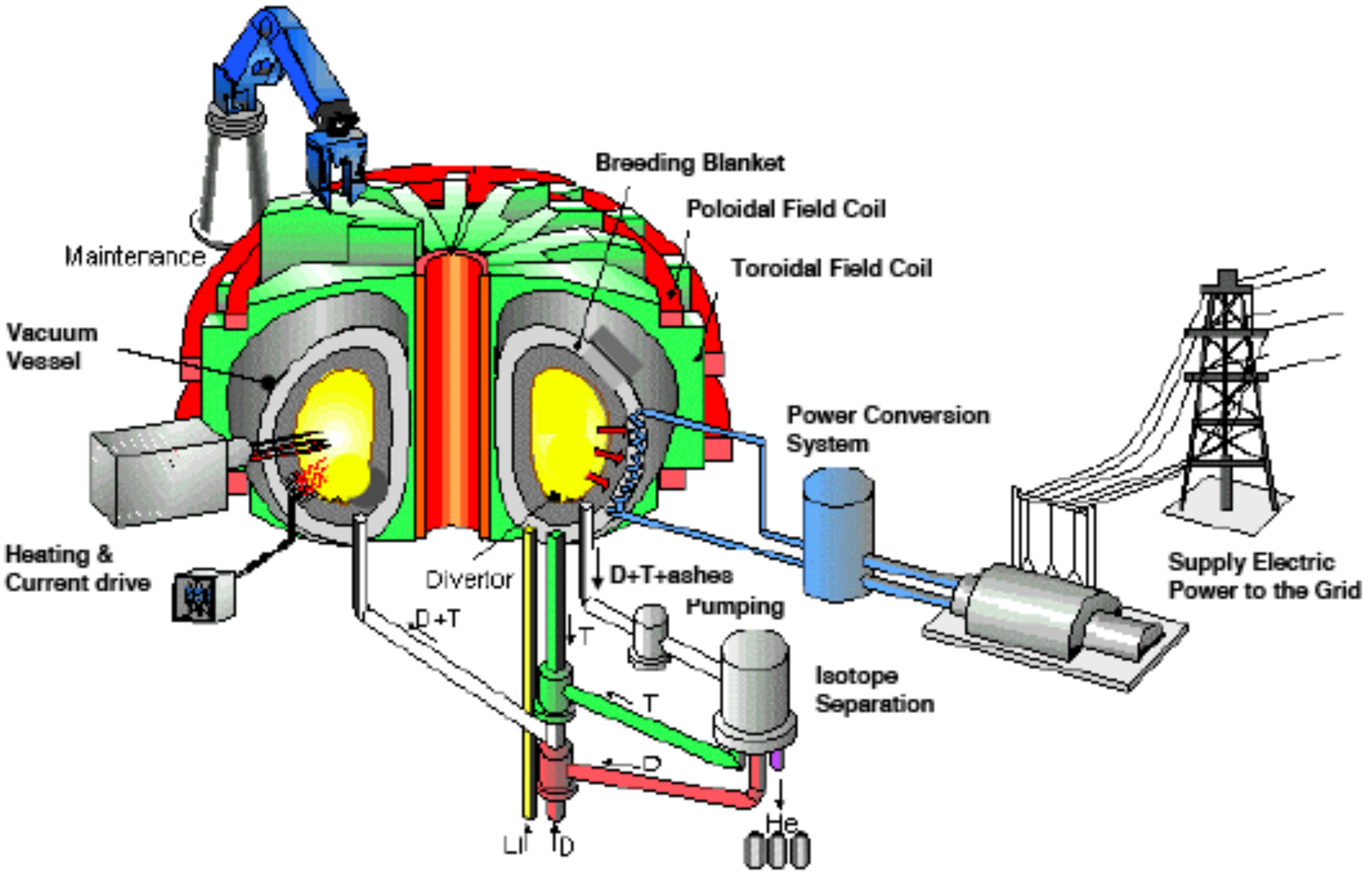
**ITER**
scientific and technological (partially) feasibility of fusion




**Fusion Power Plant**
economically acceptable, safe and environmentally friendly

# A future fusion power plant

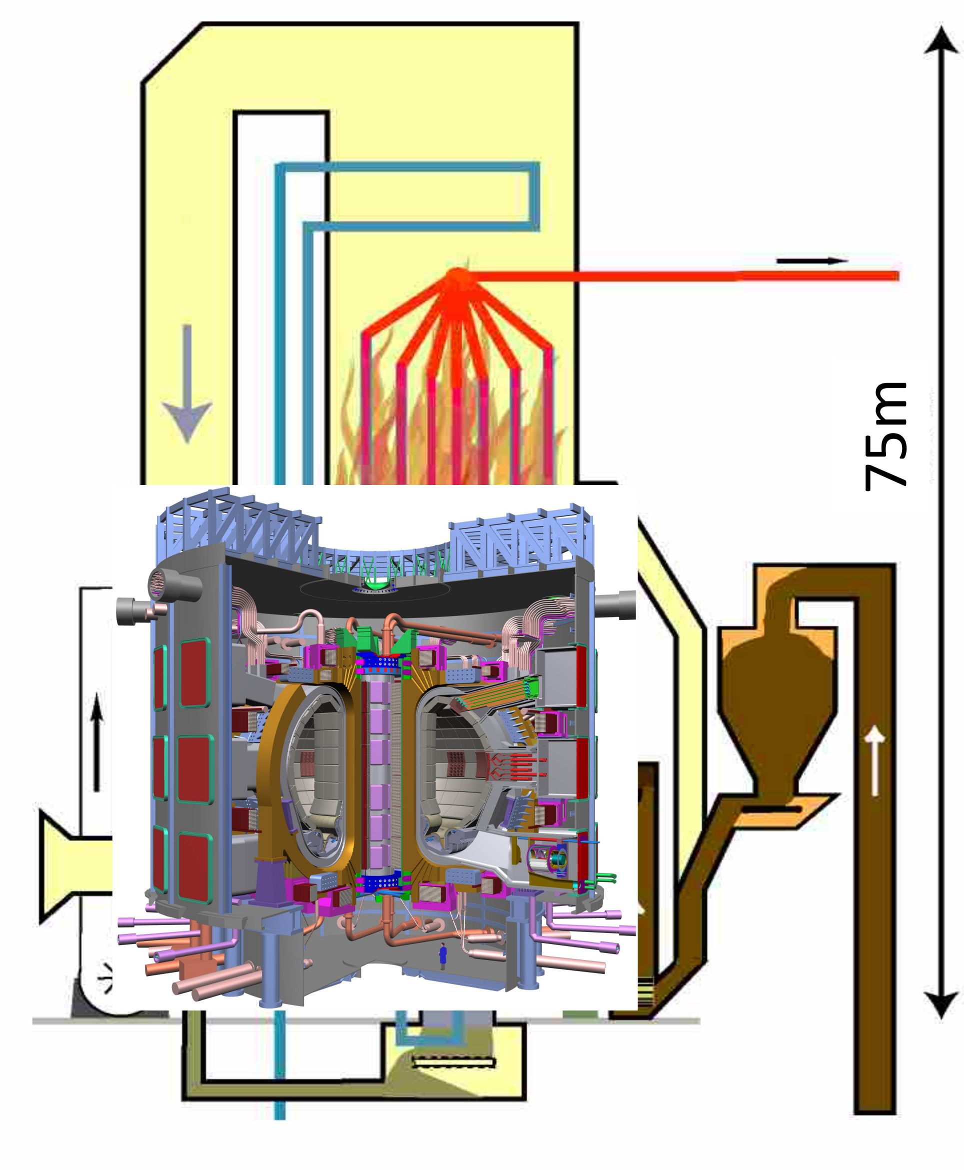
## Like any other conventional one, but with another 'oven'




**Fuel cycle integrated inside power plant:**
**D and Li basic fuels, T will be breeded from Li**

# ITER – Compare to existing systems

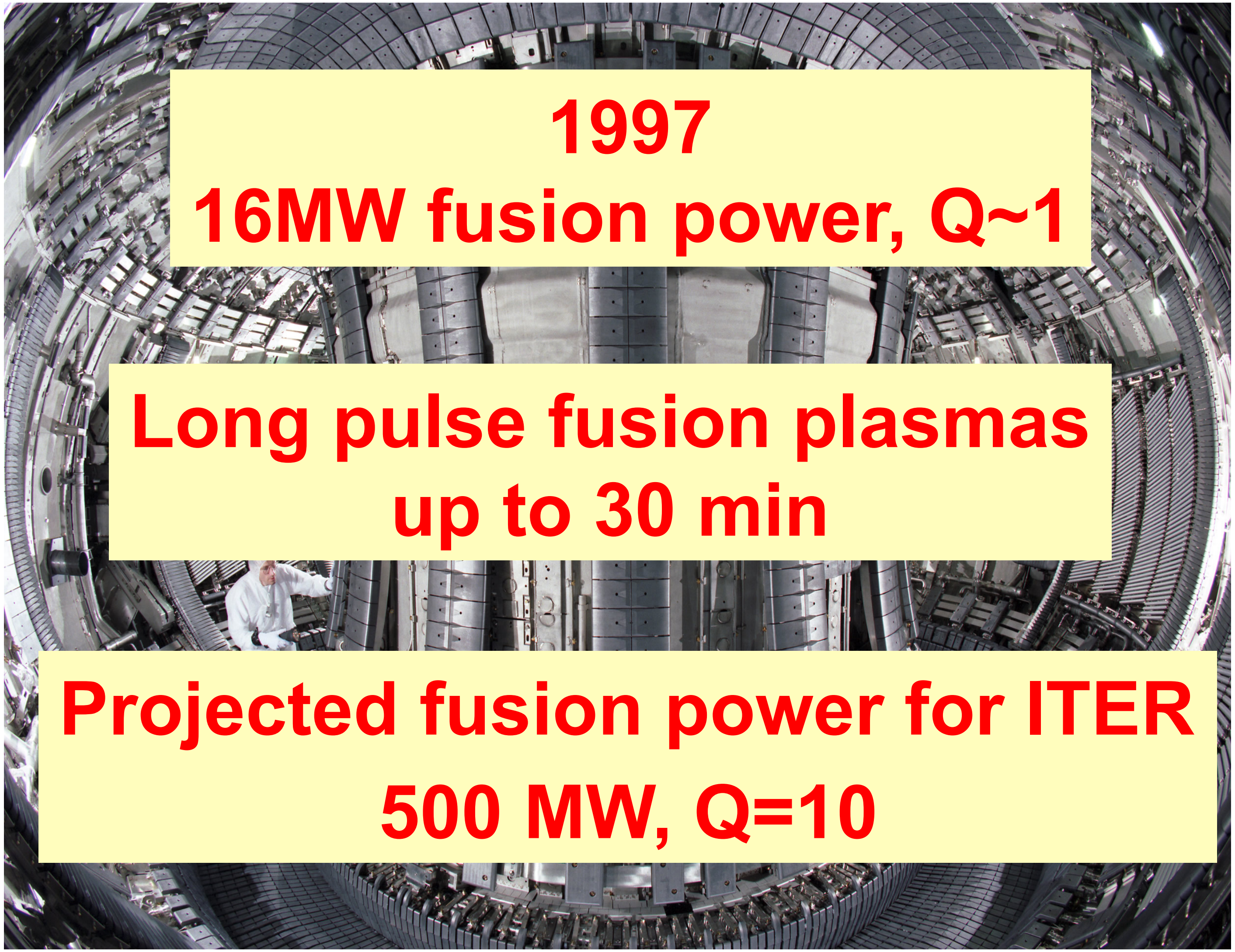
**Similar scale as a conventional large electric plant**




***Size of ITER compared to a conventional coal oven***

***(75m)***

# Main results of magnetic fusion research



# Conclusions

***For the first time in its existence, mankind has reached sufficient knowledge to confine and control matter at 200 million degrees.***

***Fusion research is rapidly progressing and important new developments have been obtained in several fields over the last few years :***

- ***plasma scenarios***
- ***heating systems***
- ***plasma diagnostics***

***ITER is the next step fusion device :***

- ***progress in fusion research depends on ITER***
- ***construction started***

***…. a true challenge for an enormous reward !!***