Energy from Fusion, from Dream to ITER

Duarte Borba
Head of Publications (on behalf of the EFDA Associate Leader for JET)
La Thuile, Aosta Valley February 27-March 5, 2005

INSTITUTO SUPERIOR TÉCNICO
Centro de Fusão Nuclear

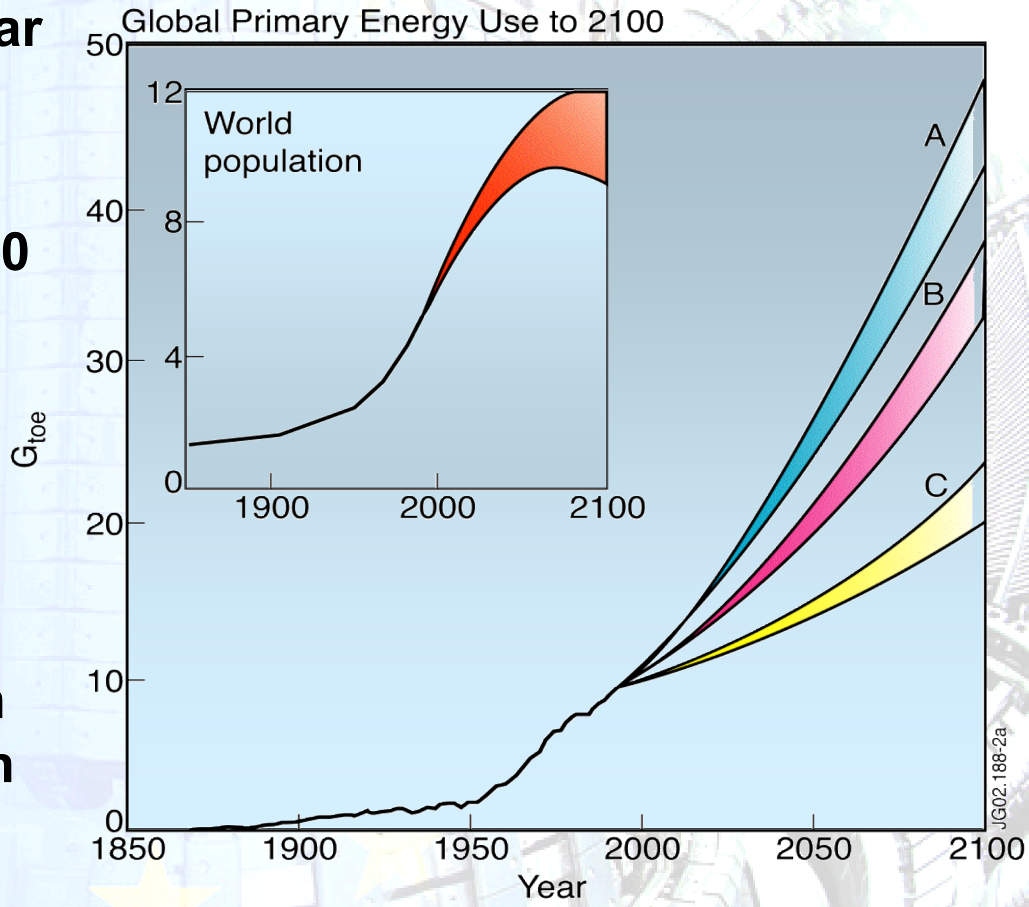
Energy from Fusion, from Dream to ITER

Outline

- World energy requirements and fusion energy
- Fusion Basics and magnetic plasma confinement
- Present status: JET and the bridge to ITER
- Burning Plasma Physics: a new scientific frontier with ITER
- Fusion Reactor and Power plant

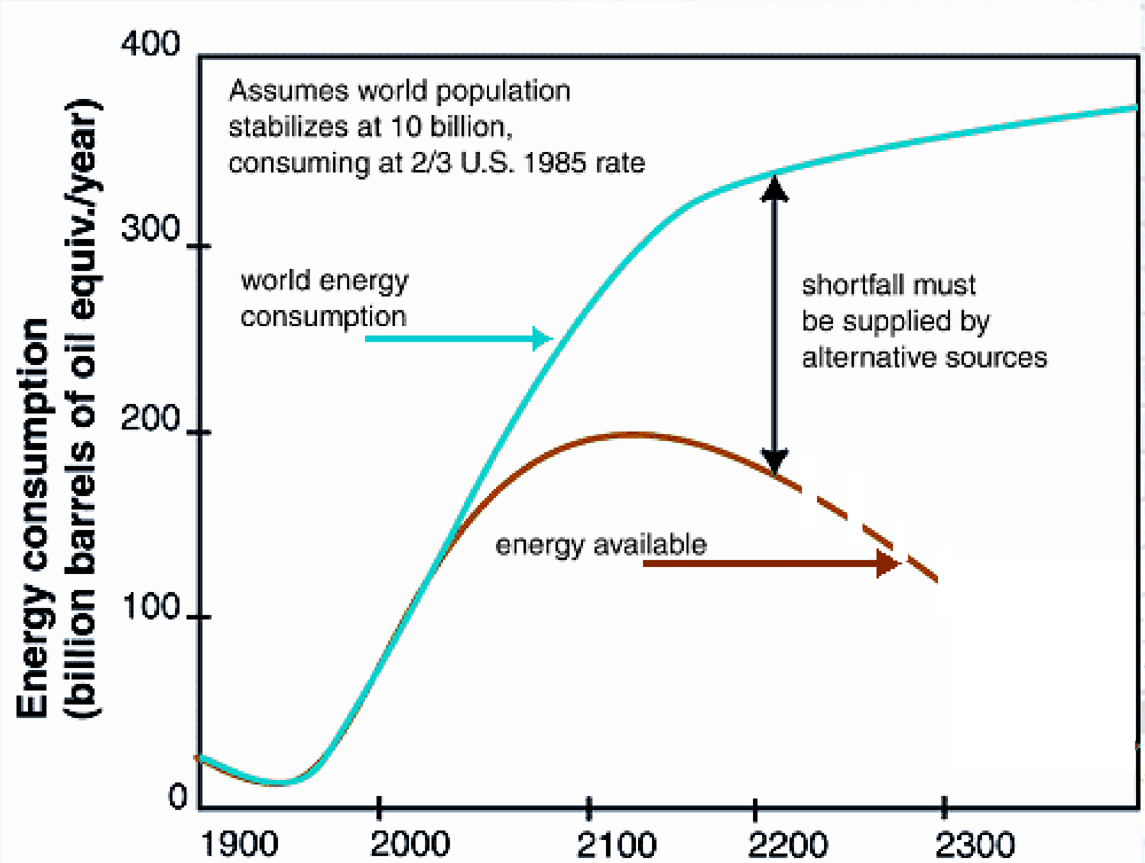
Population and Energy

- **6 billion people use each year 14 million million kWh**
- **In 50 years the world population may increase by 50 to 100%**
- **China and India (2 Billion people !) develop rapidly and need more and more energy**
- **An American uses 2 times more energy than a European who uses 5-6 times more than a Chinese**



More (and hopefully wealthier) people on earth will use more Energy

Long term Energy consumption



Fossil fuel (oil, gas and coal) sources will run out.

Conventional fission plants will exhaust uranium natural resources.

Renewable energies insufficient to meet the demands at a global scale

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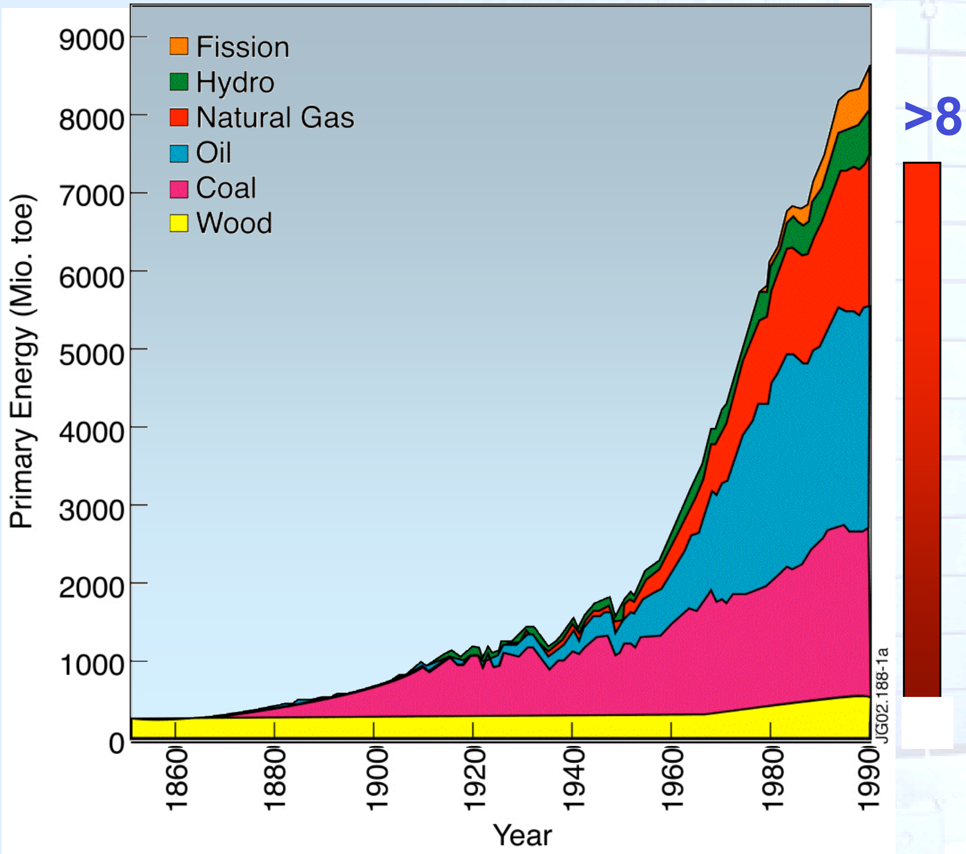
Implications of current energy sources

Currently energy is produced mainly by burning fossil fuel



Fossil fuel sources:

Will run out

Localised supply creating political tension

Much more useful applications than just burning

The greatest issue could be greenhouse gases

~4 tons of CO2 per person per year in average over the world !

Your car produces… 3-4 times its weight in CO2/year (10 000 miles/y)

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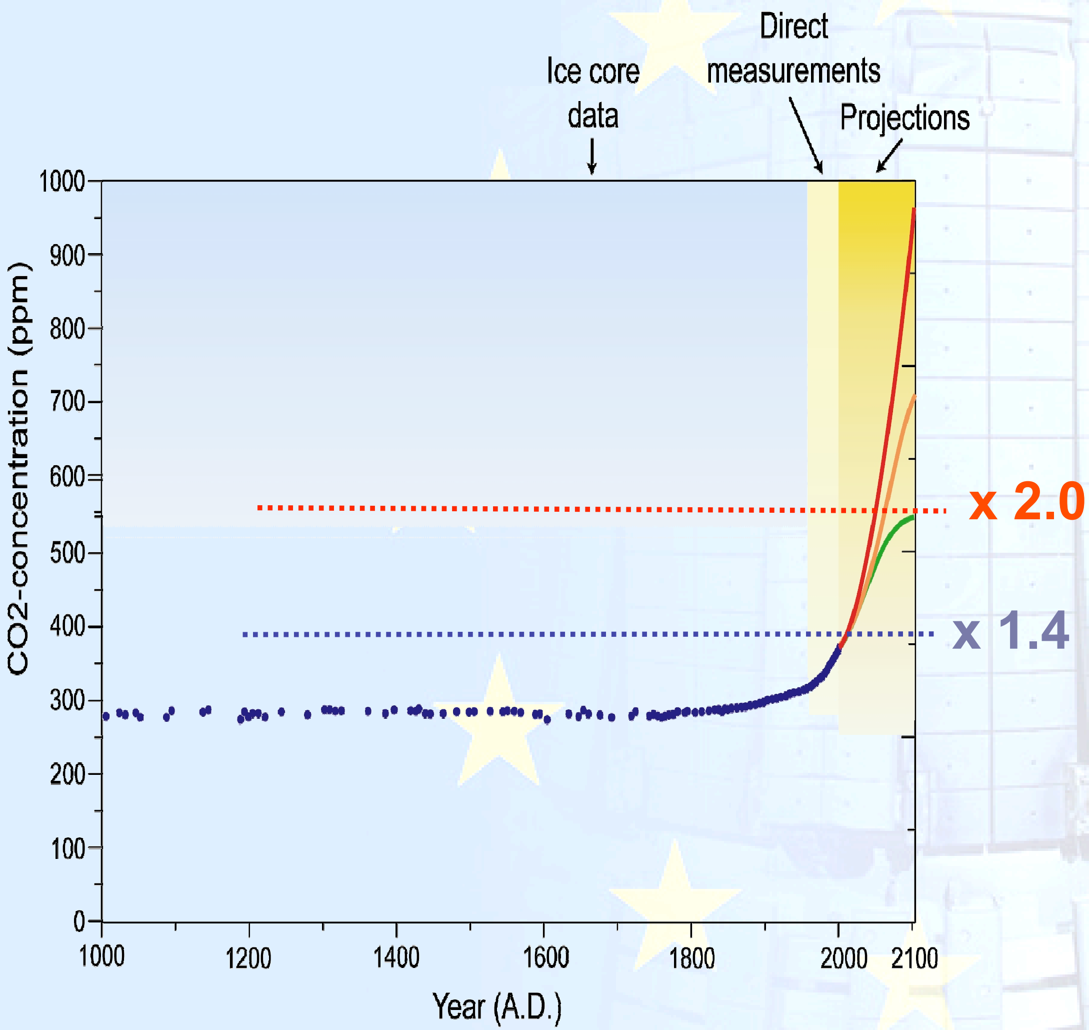
Climate implications of burning fossil fuels

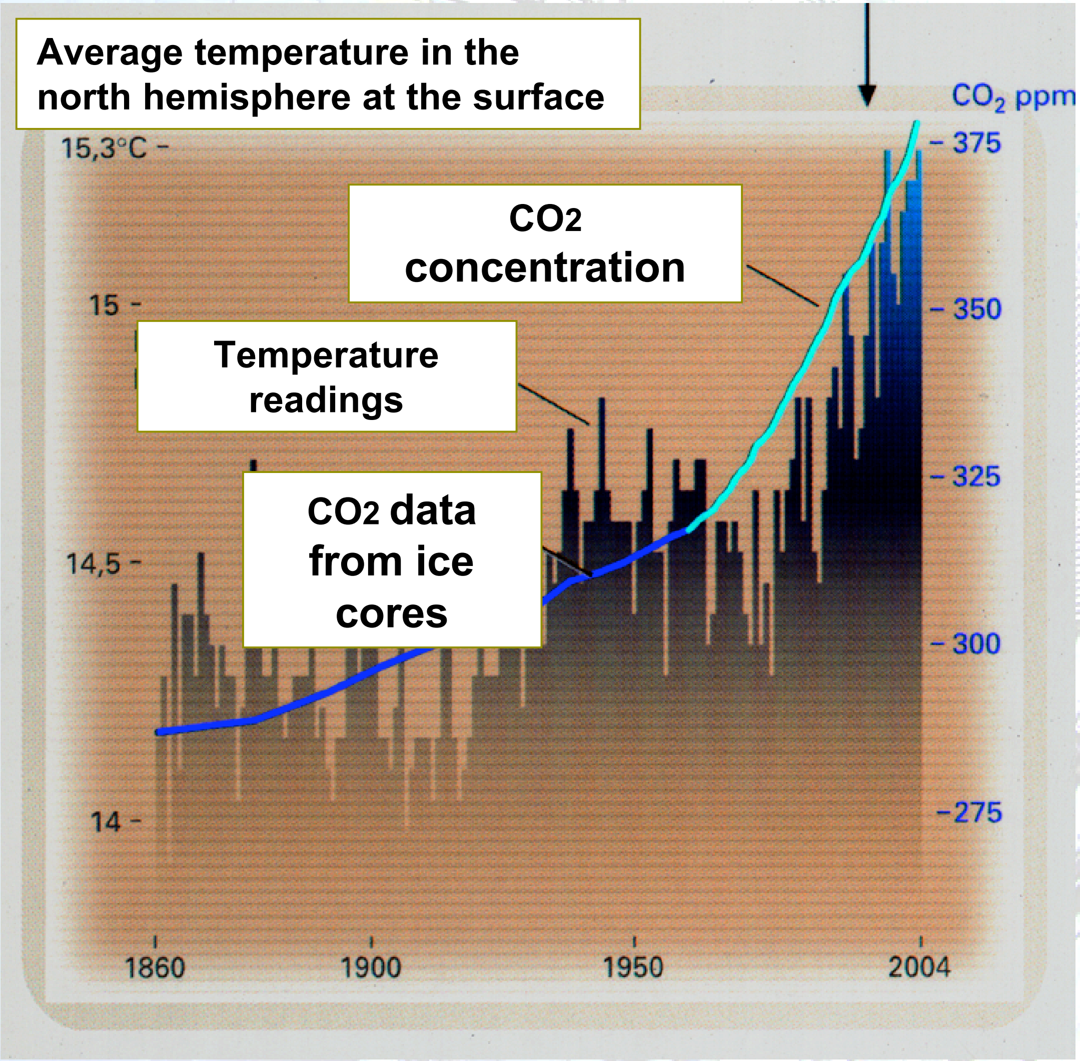


CO_2 in the atmosphere increased by 40% over the last 100 years

Predicted to at least double the natural value within the next 50 years

Global Warming is happening

- Global warming is already happening
- There is evidence that the main cause of recent global warming is atmospheric pollution



Potential Sources of Energy in XXI century

- **Nuclear Fission** (Long term storage of high level radioactive waste)
- **Fossil fuels** (Coal, Gas) (Green house gas emissions and Global warming)
- **Renewables** (Solar,Wind) (not sufficient for very large energy demands peak power >>1GW)
- **Nuclear Fusion** (Safe & low level radioactive waste, no atmospheric pollution, **still to be demonstrated**)

Advantages of Fusion energy

- Fuel abundant (available world-wide)
- Deuterium available for millions of years
- Lithium (to produce Tritium) available for thousands of years
- No Greenhouse gases (CO, CO2) and no acid rain (SO2, NO2)
- Short life radioactivity (associated with plant activation)
- Fuel cycle inside the reactor, no need for transport of activated materials

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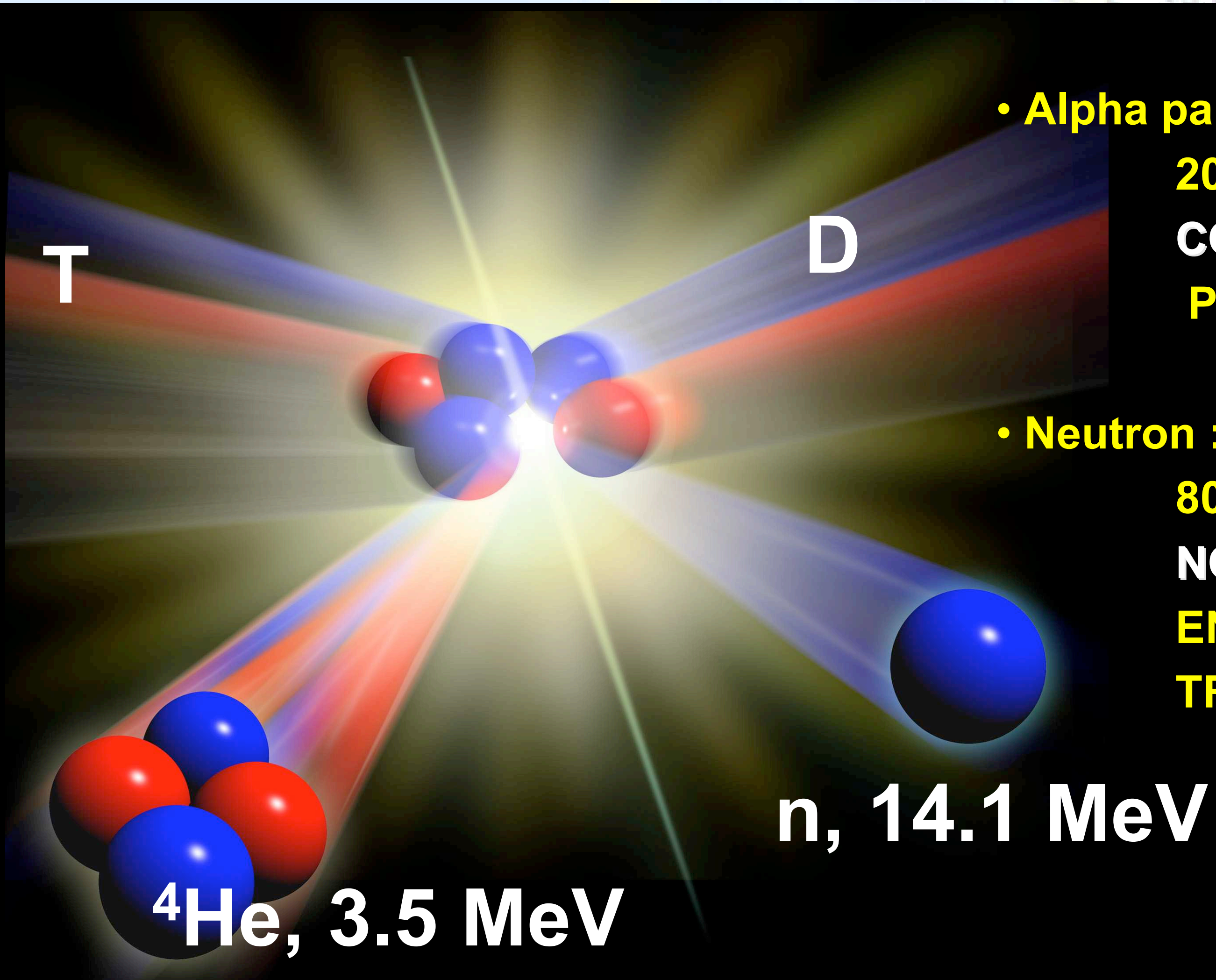
D-T Fusion Reaction: $D + T \rightarrow {}^4He + n$

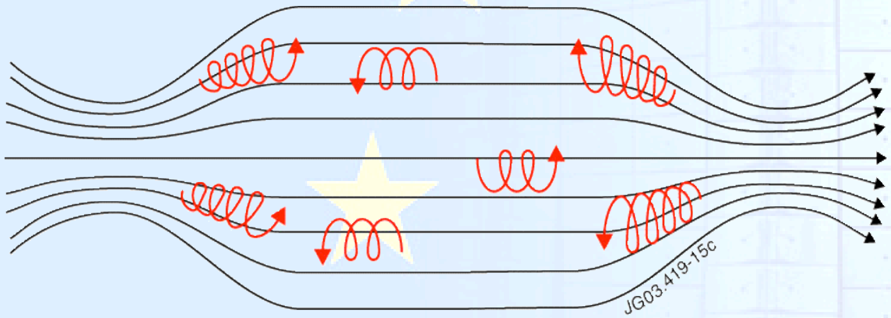


- Alpha particle :
  - 20 % of reaction energy
  - CONFINED
  - PLASMA SELF HEATING
- Neutron :
  - 80 % of reaction energy
  - NOT CONFINED
  - ENERGY OUTPUT and
  - TRITIUM PRODUCTION

Magnetic confinement

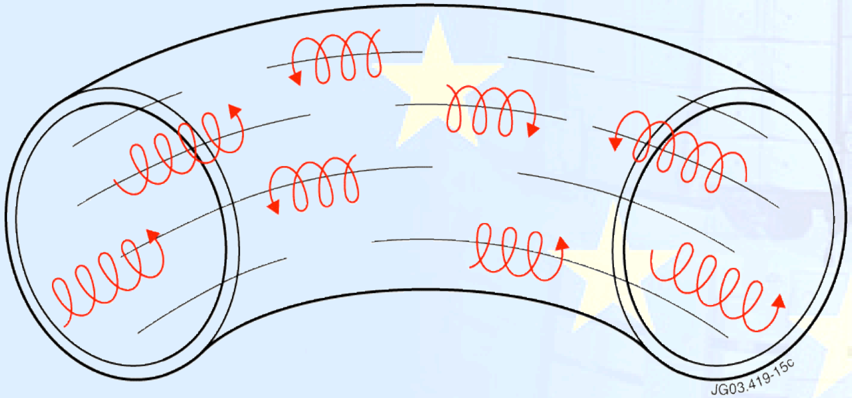
Particles move freely along field lines: how to stop the end losses ?

two solutions



- Pinching the field lines at the end -> reflection ("mirror")

  linear arrangement



- Closing the field lines on themselves

  toroidal confinement

- However: a pure toroidal field does not work

- Need a helical field

Containment of hot plasmas : tokamak

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

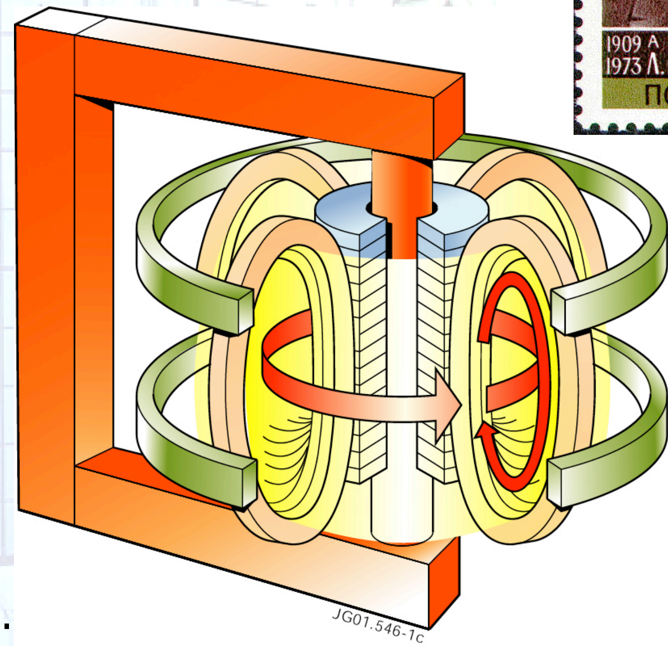
toroidalnaya **ka**mera, **ma**gnitnaya **k**atushka

meaning

"**toroidal chamber**"

and

"**magnetic coil**"

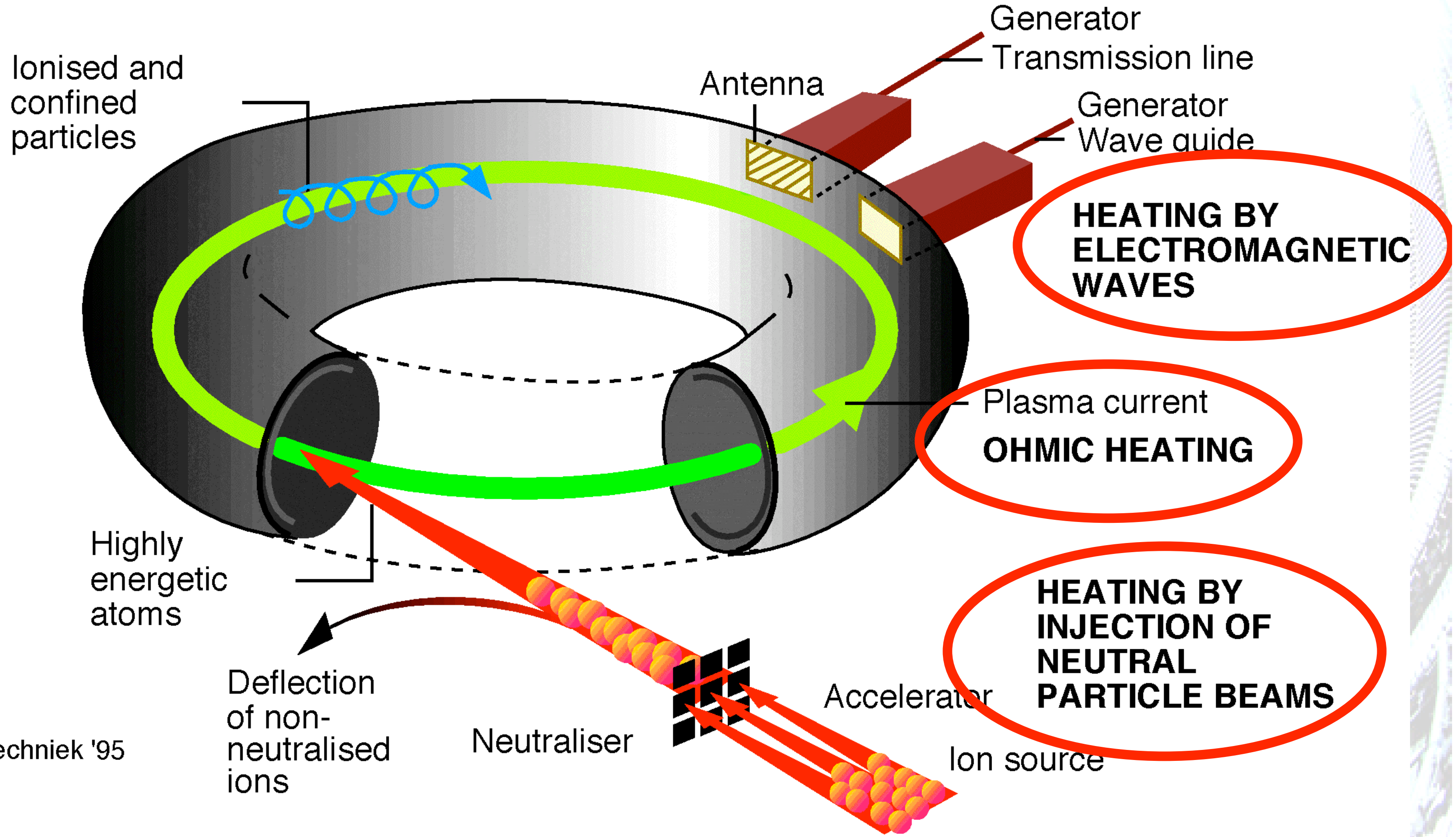


- A tokamak is a toroidal plasma confinement device with:
  - External coils to provide a **toroidal magnetic field**.
  - A transformer with a primary winding to produce a toroidal current in the plasma.
  - The current generates a **poloidal magnetic field** and therefore **twisted field lines**.
  - The current provides **plasma heating**

Quality of confinement ≡ Energy confinement time (τ_E)

How to obtain the ultra high temperatures needed ?

Ohmic heating: $\eta \propto T^{-3/2}$ => limited to T~1keV, additional heating needed



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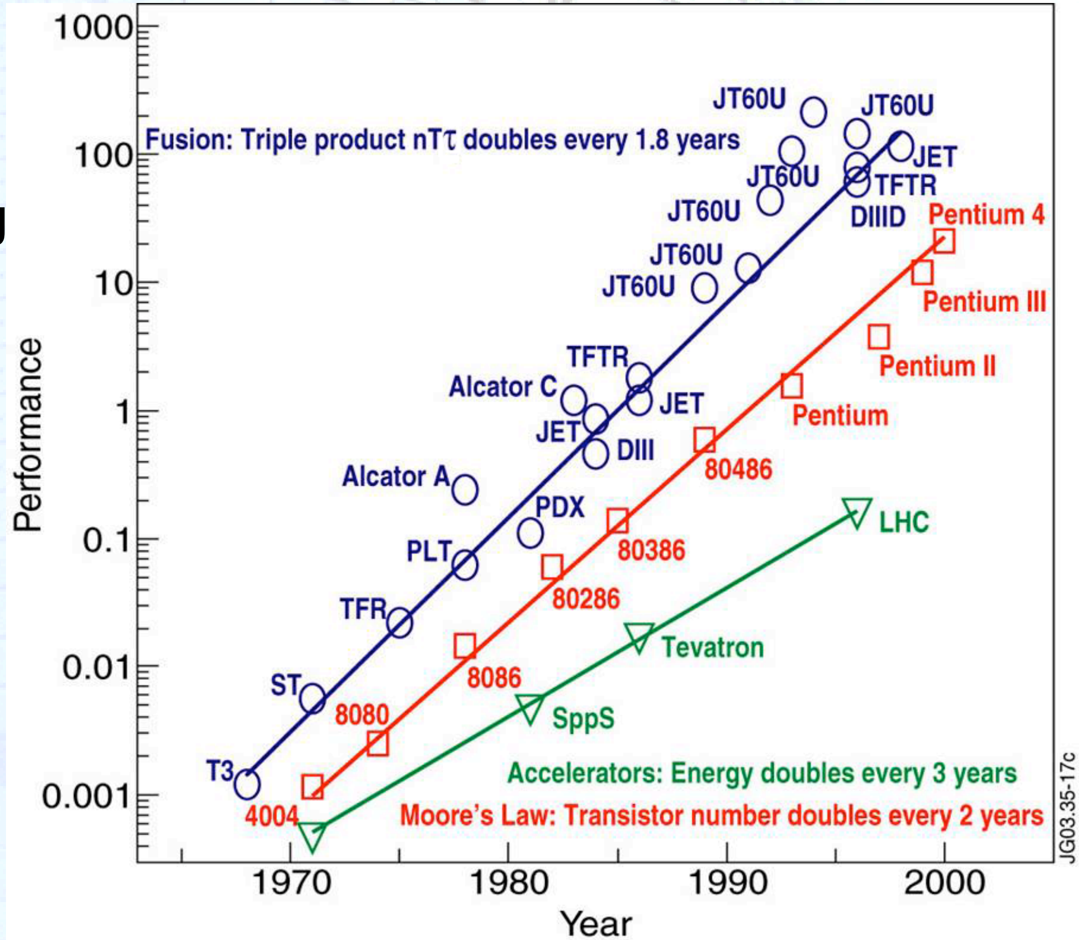
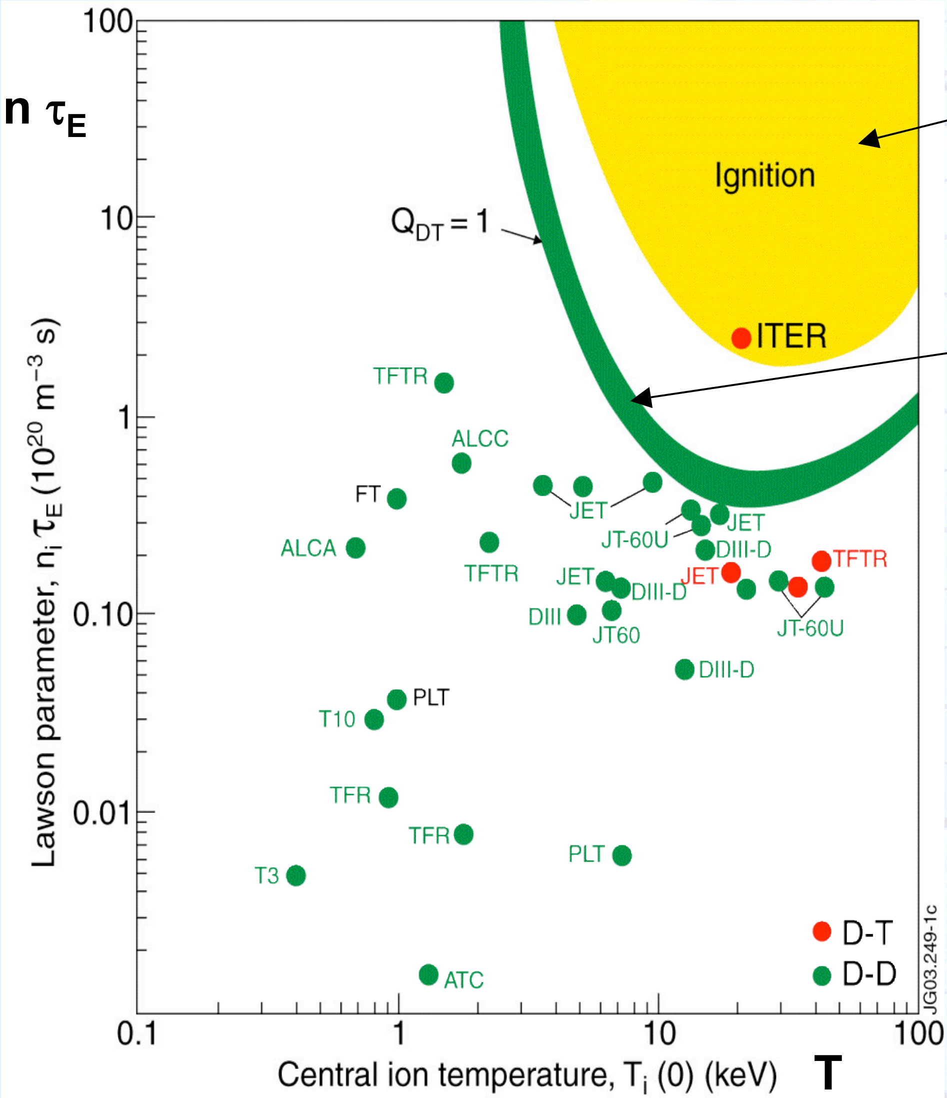
Fusion made significant progress

- **Progress in fusion can be compared with the computing power and particle physics accelerator energy**

- **Present machines produce significant fusion power "TFTR (US) 10MW in 1994" and "JET(EU) 16MW in 1997"**



Conditions for Fusion (Lawson Criteria)



$n\ \tau_E > f\ (T)$
(external power = 0)

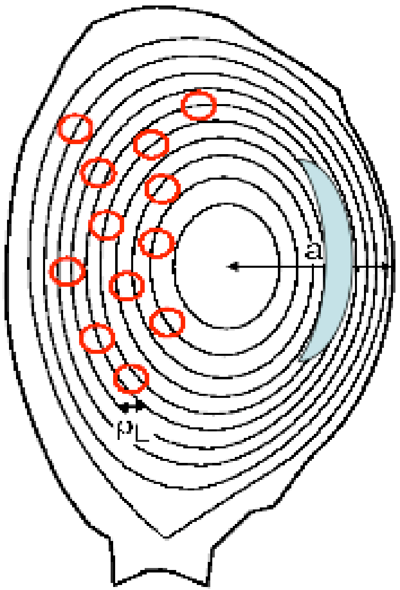
$n\ \tau_E > f\ (T,\ Q = P_{fus}/P_{ext})$
(external power $\neq$ 0)

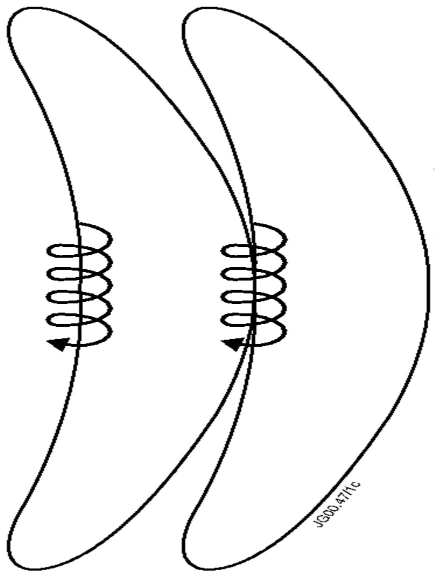
$n \times \tau_E > f\ (T)$
sometimes
also transformed into

(taking into account temperature dependence near minimum)

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

Characteristic dimensionless variables in plasma physics





$\rho^* \propto \frac{\text{particle gyro radius}}{\text{minor radius}} = \frac{\rho_L}{a}$

- Diffusion Processes
- MHD

$\nu^* = \frac{\text{collision frequency}}{\text{bounce frequency}}$

•Diffusion Processes

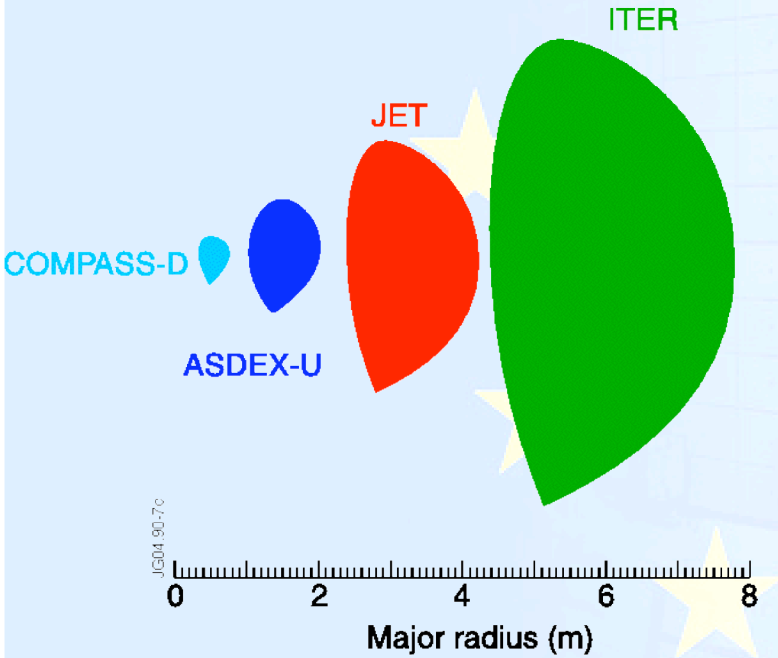
$\beta_N \propto \frac{\text{plasma pressure}}{\text{magnetic pressure}}$

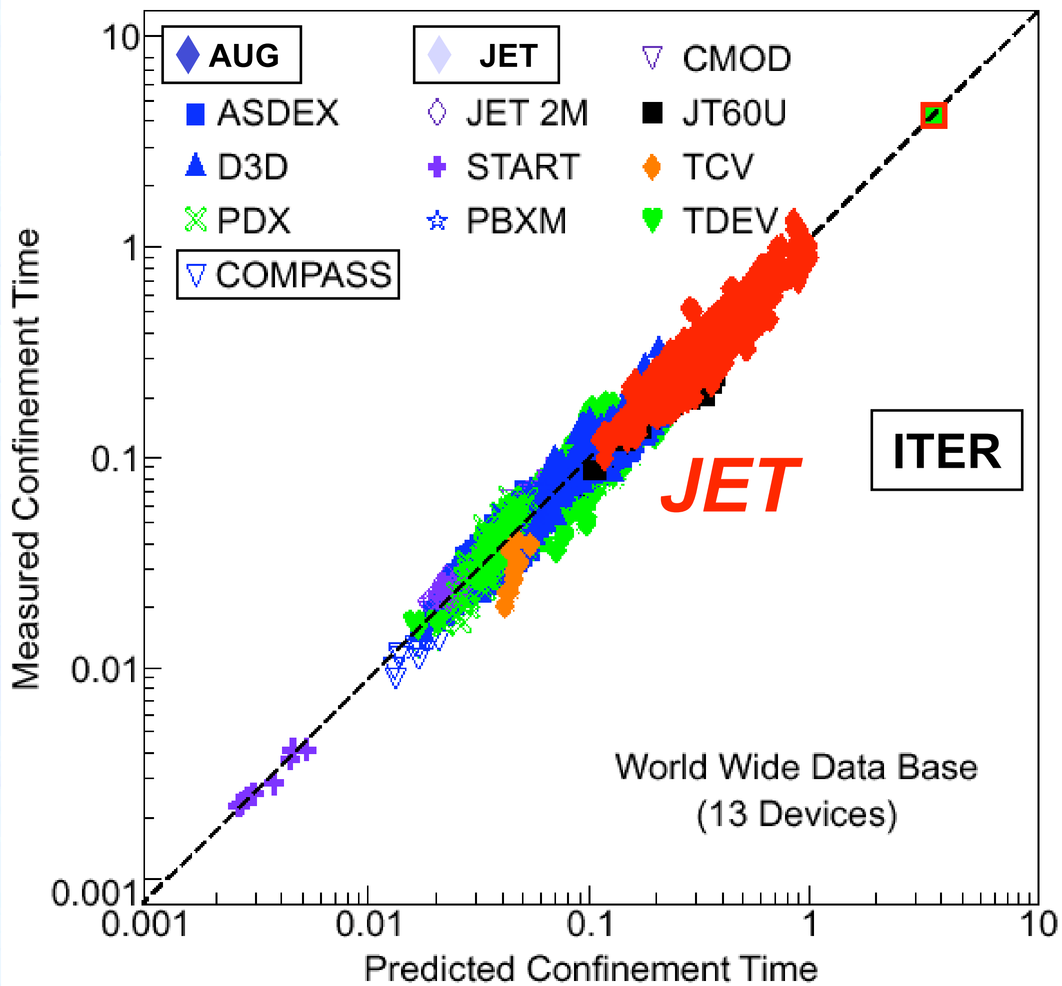
- Stability, MHD
- Fusion Power $\propto \beta_N^2$

_E energy confinement time scaling law: _c_E ~ $\_^{-0.66}$ $\_\_^{-2.8}$ $\_\_^{-0.09}$

Prediction of ITER performance

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





$$_E = 0.0228\ I^{0.86}\ B^{0.21}\ R^{1.31}\ n^{0.40}\ a^{-0.99}\ A^{0.84}\ M^{0.08}\ P^{-0.65}$$

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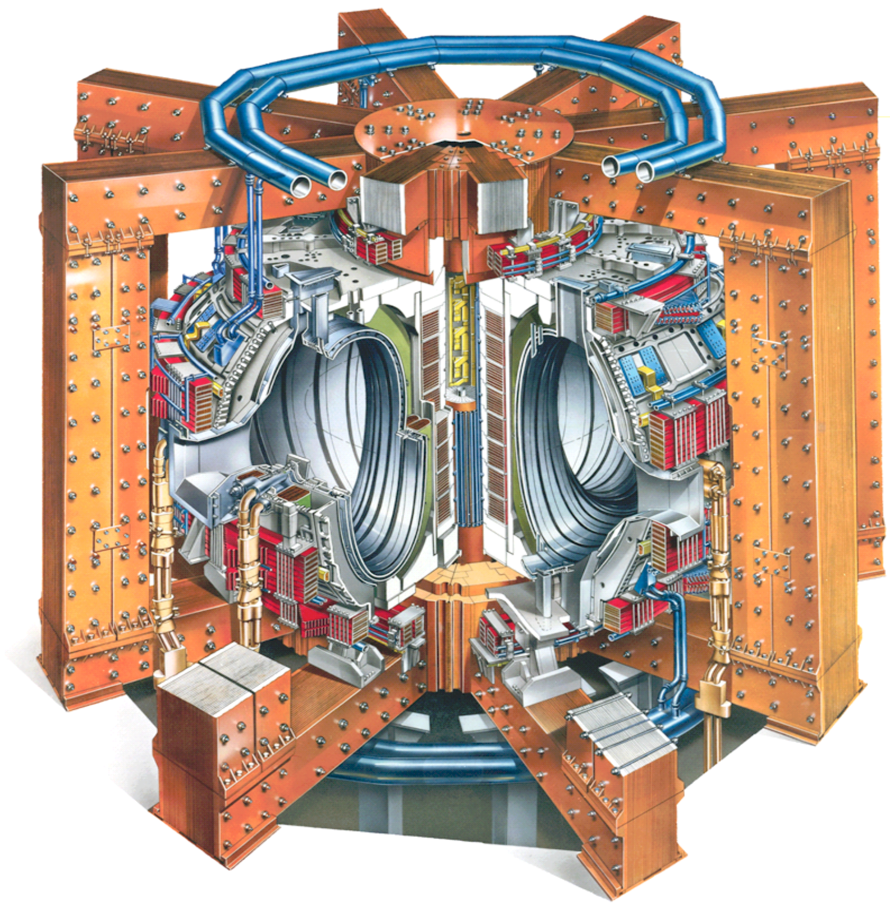
JET and the other tokamaks currently in operation*

Maximum Plasma Current	Europe	Japan	USA	Russian Federation	China
Up to 5 MA D-T capability Be capability	JET	-----	-----	-----	-----
Up to 3MA	-----	JT-60U	-----	-----	-----
Between 1 MA and 2MA	ASDEX-Upgrade, FTU MAST, TORE-SUPRA	-----	NSTX DIII-D, C-MOD	-----	-----
Between 0.5MA and 1MA	TEXTOR, TCV	-----	-----	T-10	-----
0.5 MA and less	COMPASS-D CASTOR, ISTTOK	TRIAM-1M JFT-2M	HBT-EP ET	T-11M, TUMAN-3M GLOBUS-M	HT-7, HT-6M, HL-1M HL-2A, CT-6B, KT-5C

***New super-conducting tokamaks are in construction in China (EAST, SUNIST) and South Korea (KSTAR)**

The Joint European Torus (JET) the largest tokamak worldwide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Plasma operation closest to ITER

Torus radius	3.1 m *(ITER 6m)*
Vacuum vessel wide	3.96m high x 2.4m
Plasma volume	80 m^3 - 100 m^3
Plasma current	up to 5 MA *(ITER 17MA)* in present configurations
Magnetic field	up to 4 Tesla *(ITER 5.3T)*

Unique technical capabilities worldwide:

- Tritium operation
- Beryllium (ITER First Wall)
- Remote Handling

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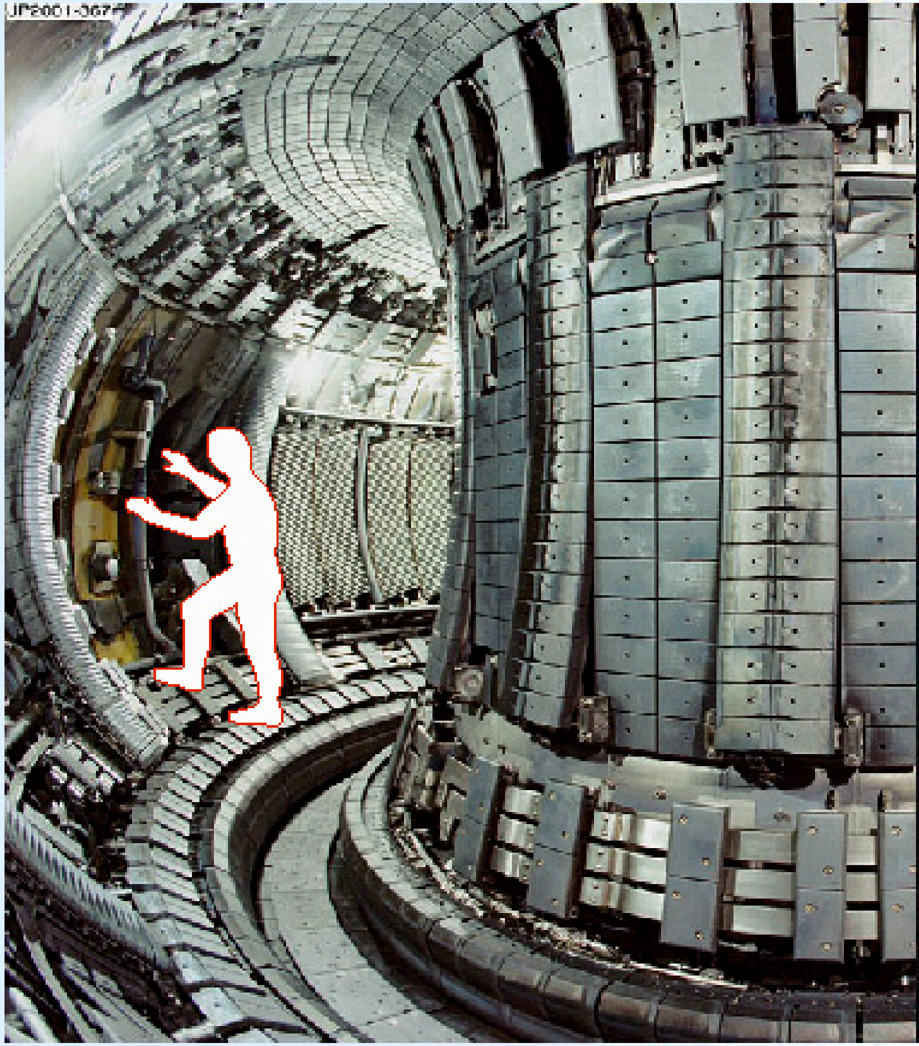
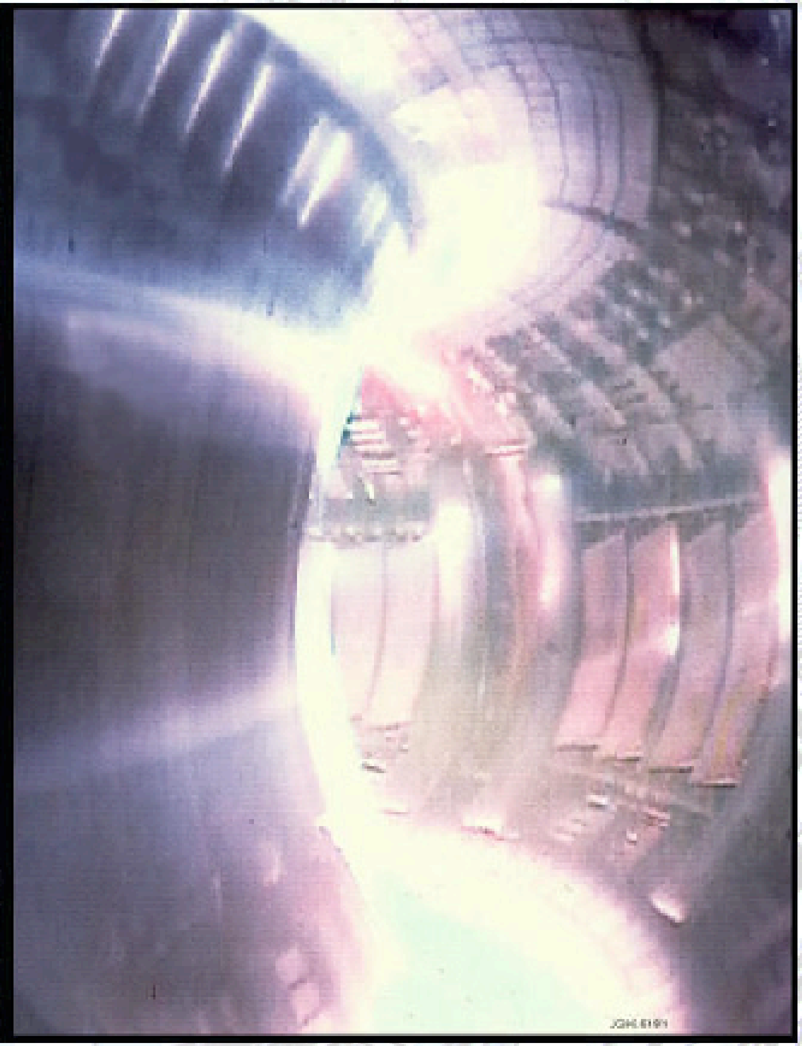
Inside JET without and with plasma





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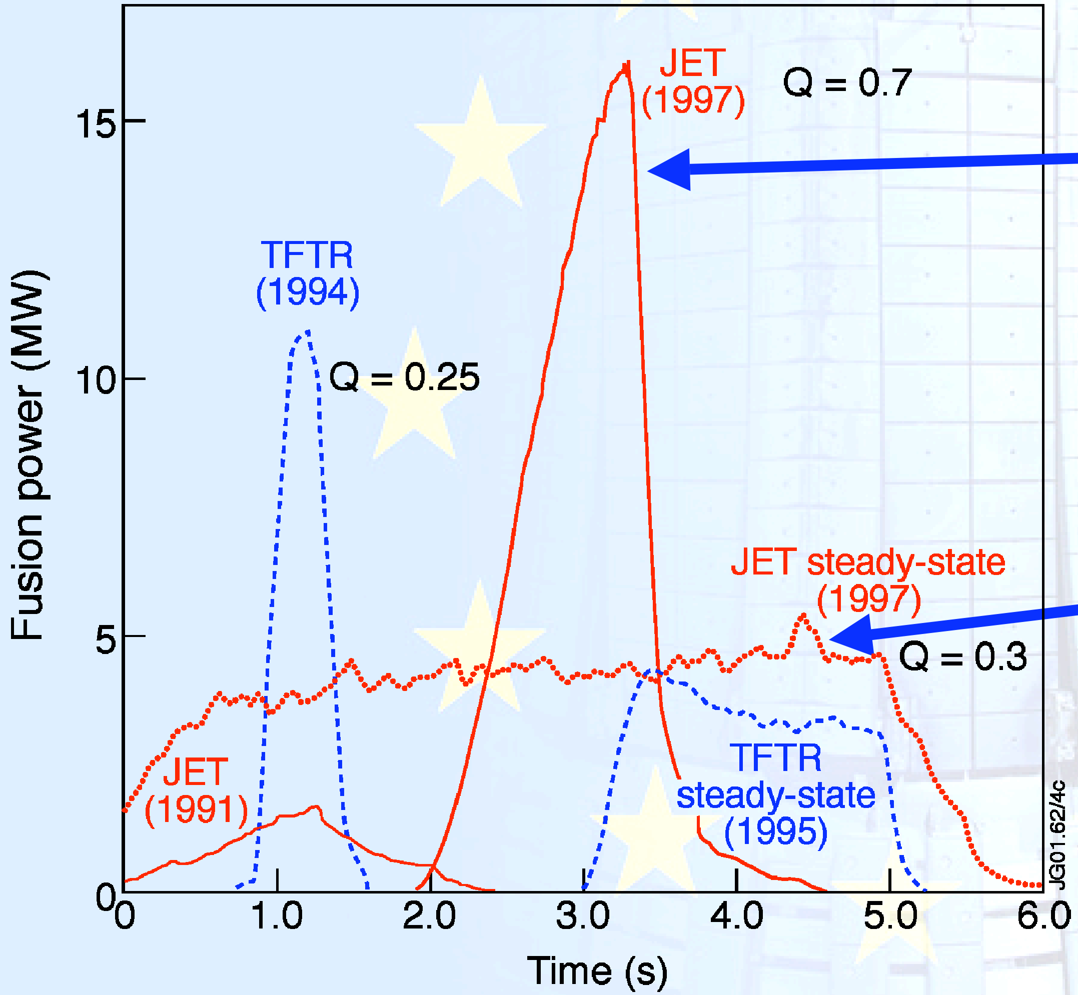
Successful D-T Operation on JET

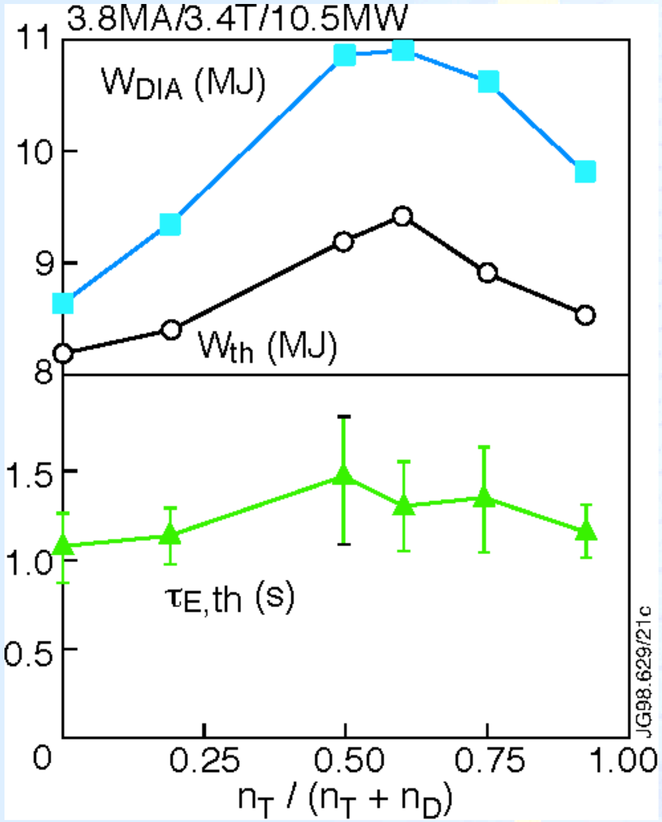
D-T plasma discharges at JET and TFTR (50% D-50% T) obtained in 1991-1997

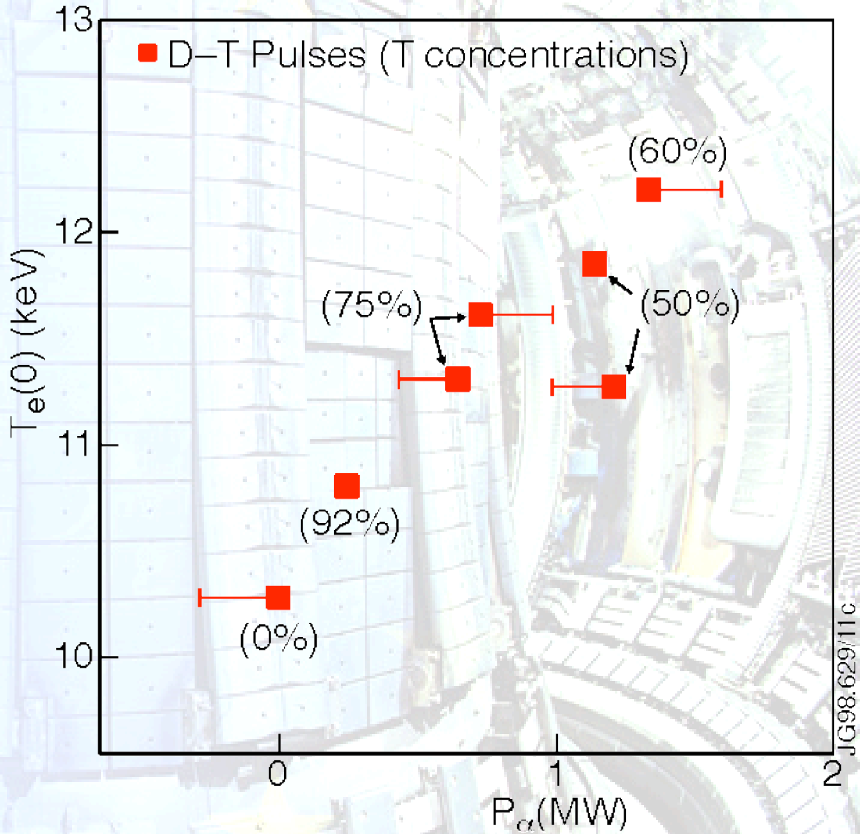


16 MW Fusion peak power at JET

4.5 MW Steady state Fusion Power (22 MJoule of fusion Energy)

Alpha heating demonstrated on JET (1997)





- $\eta = n_T/(n_D+n_T)$ => $P_{fusion} \sim \eta(1-\eta)$ optimum D/T mix at $\eta \sim 0.5$
- Highest Electron Temperature with optimum D/T mix

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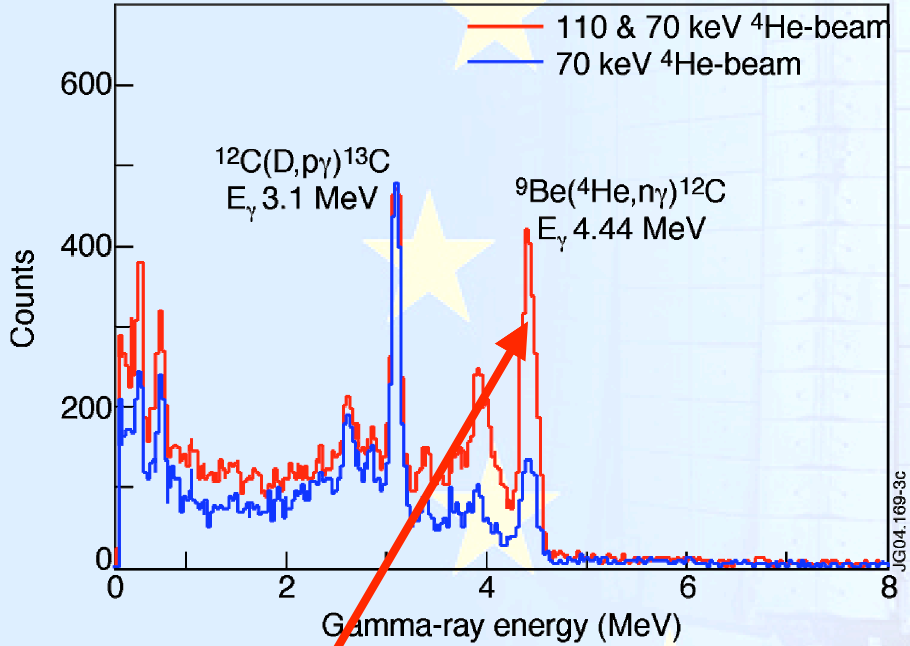
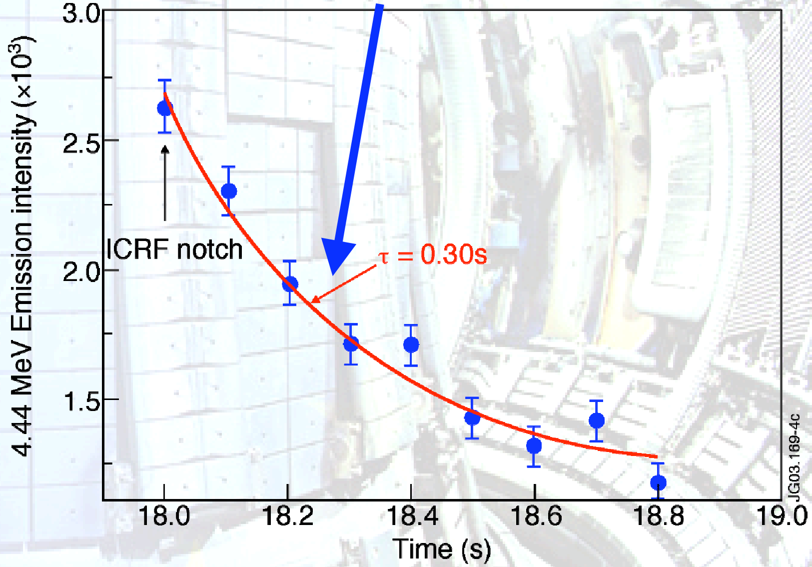
γ-spectroscopy: detection of fast α- particles

First direct measurements of α-particle slowing down (in D-T October 2003 and with α simulation February 2004)



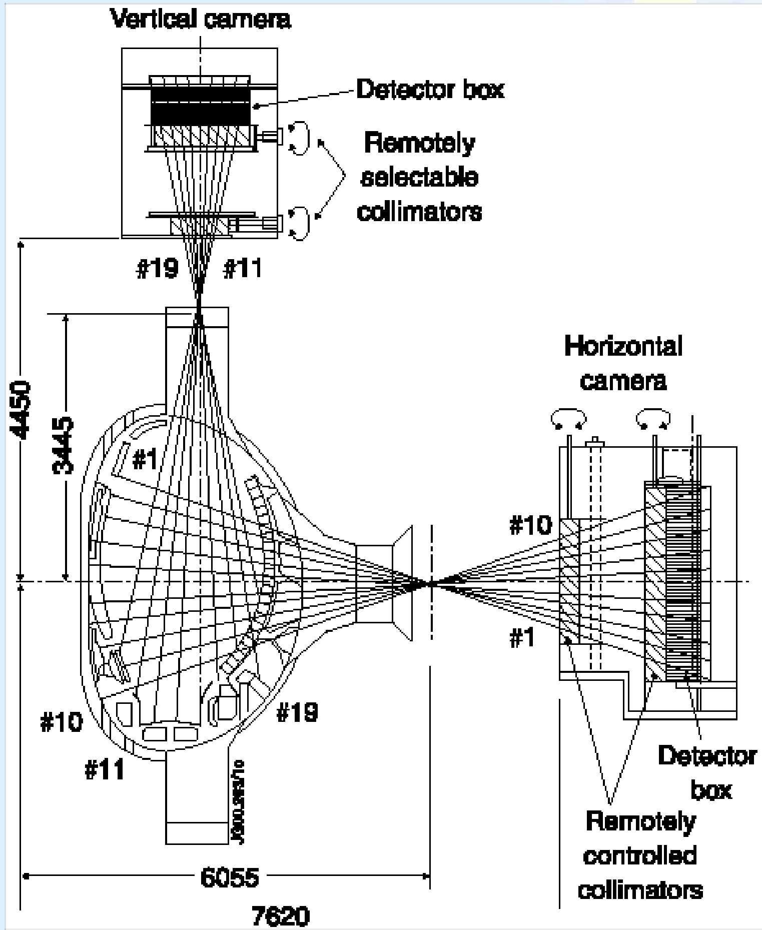
α slowing down directly measured

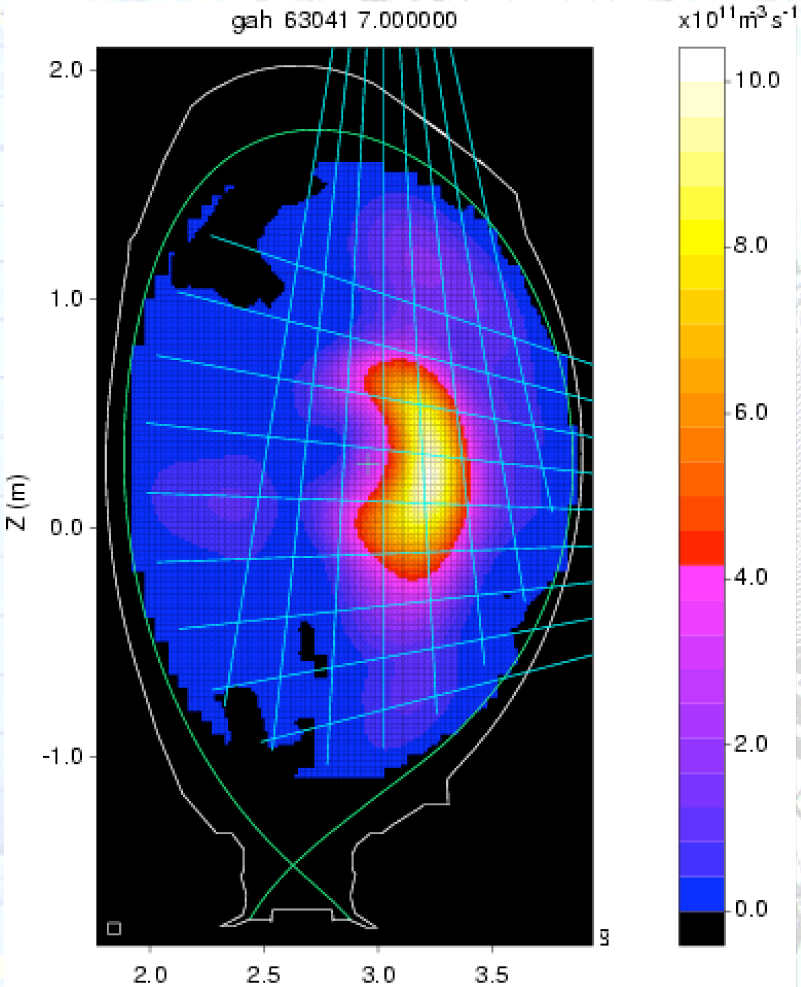


γ from Be-α reactions (E_{α} > 1.7 MeV)

Very powerful technique used to study α slow-down in all plasma configurations foreseen for ITER

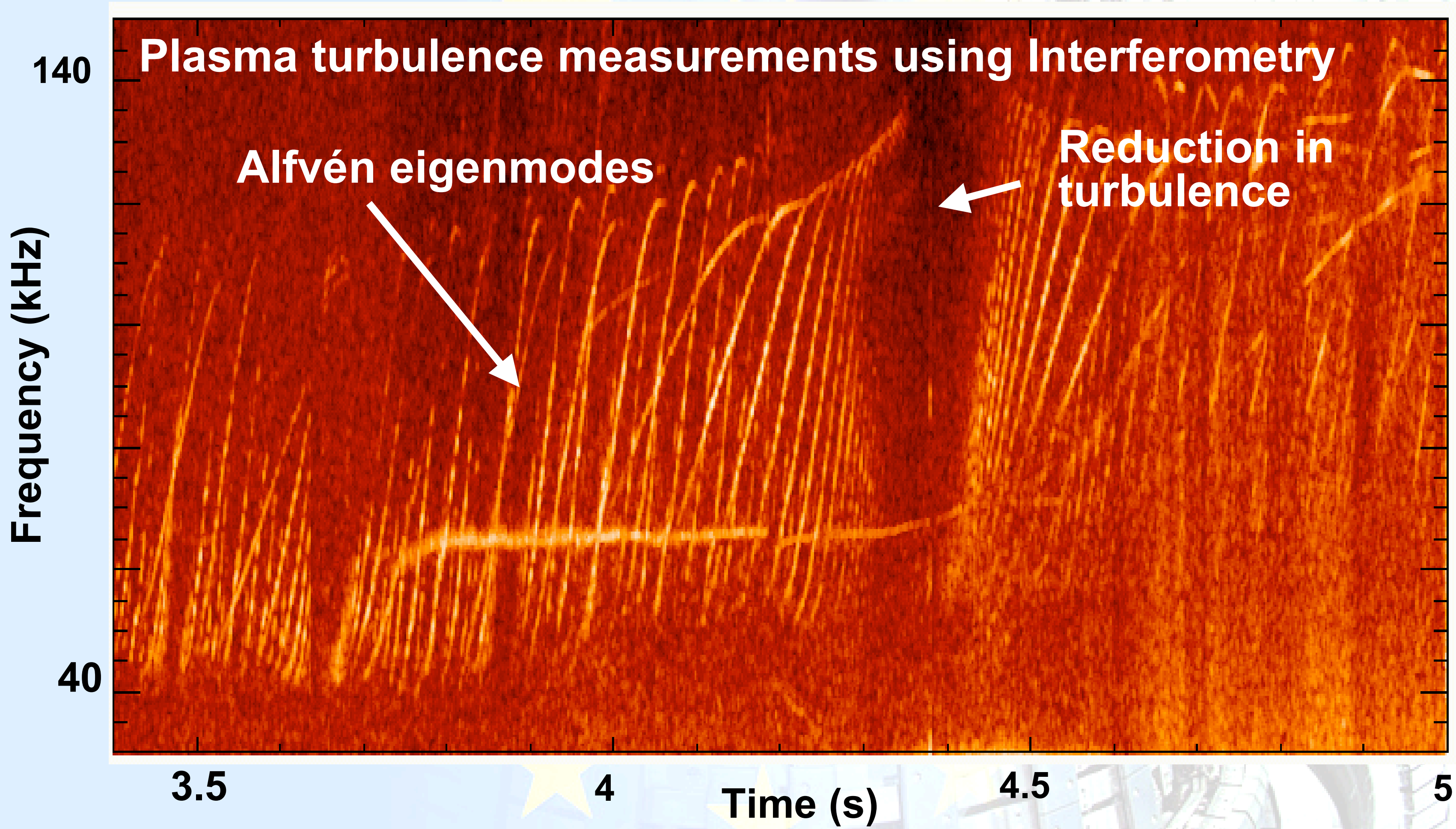
γ-spectroscopy: tomography of fast α- distribution





α particle density measured by γ emission in agreement with simulation (October 2003)

Fast particles have a strong impact on plasma stability



- **Alfvén eigenmodes may cause potential α redistribution / losses**

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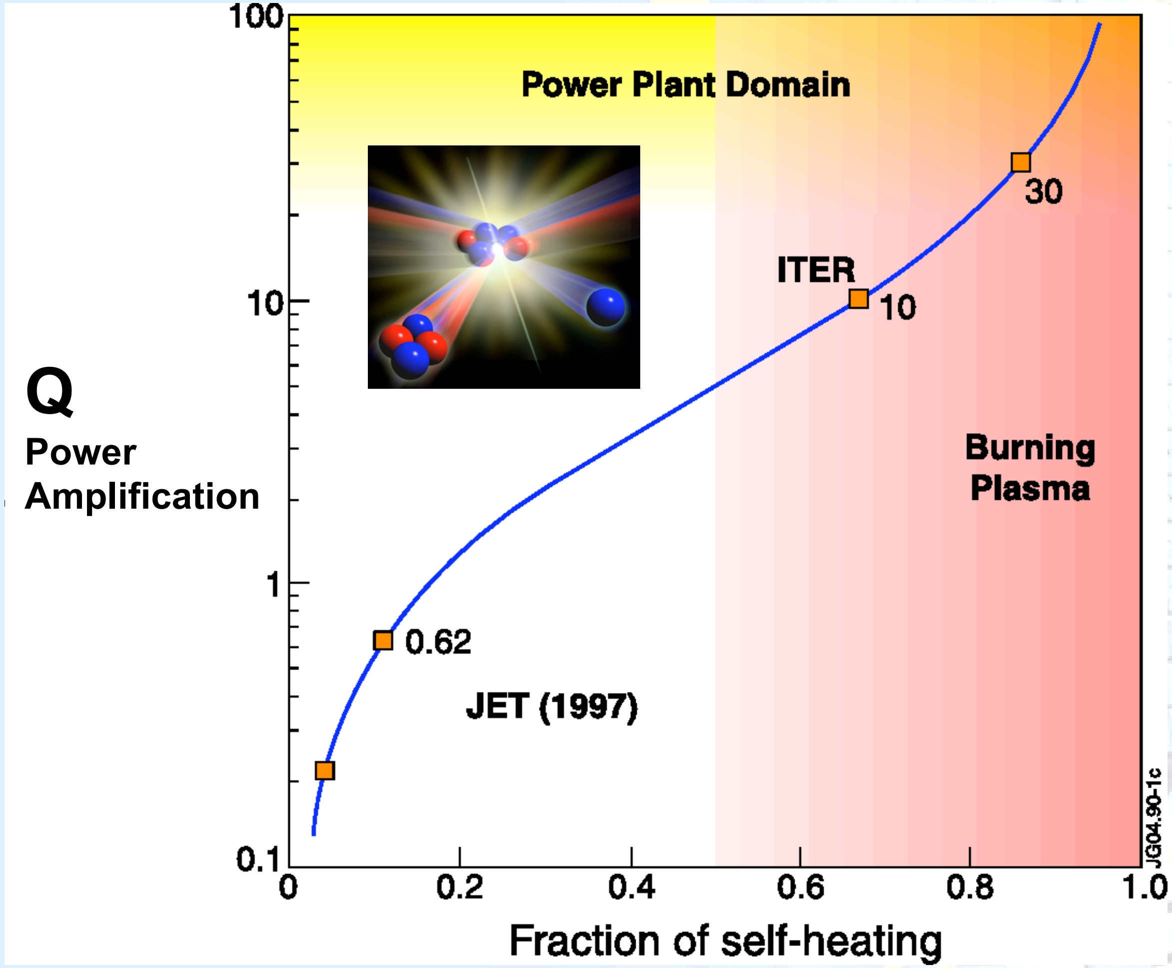
ITER : a burning plasma



fα

Power amplification
(engineering parameter, related to plant efficiency)

$Q = P_{fusion}/P_{ext}$

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

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

with Q > 10, ITER will provide access to plasmas with adequate self heating (fα > 2/3)

Planned: International Tokamak Experimental Reactor (ITER) is the next experimental step required for demonstration of fusion as a potential energy source.

ITER Parameters

R (m)	6.2
a (m)	2
flat-top length (s)	**2000**
B_t (T)	5.3
I_P (MA)	15(17)
P_{fus} (MW)	**410**
P_{aux} (MW)	40-90
P_α (MW)	85
$Q(P_{fus}/P_{in})$	**10**
β_T, β_P	2.5%, 0.7

ITER Detailed Technical Objectives

- Fusion power gain **$Q = P_{fusion}/P_{external} = 10$**
- Test essential technologies in reactor-relevant conditions
- Test high-heat-flux and nuclear components
- Demonstrate safety and environmental acceptability of fusion

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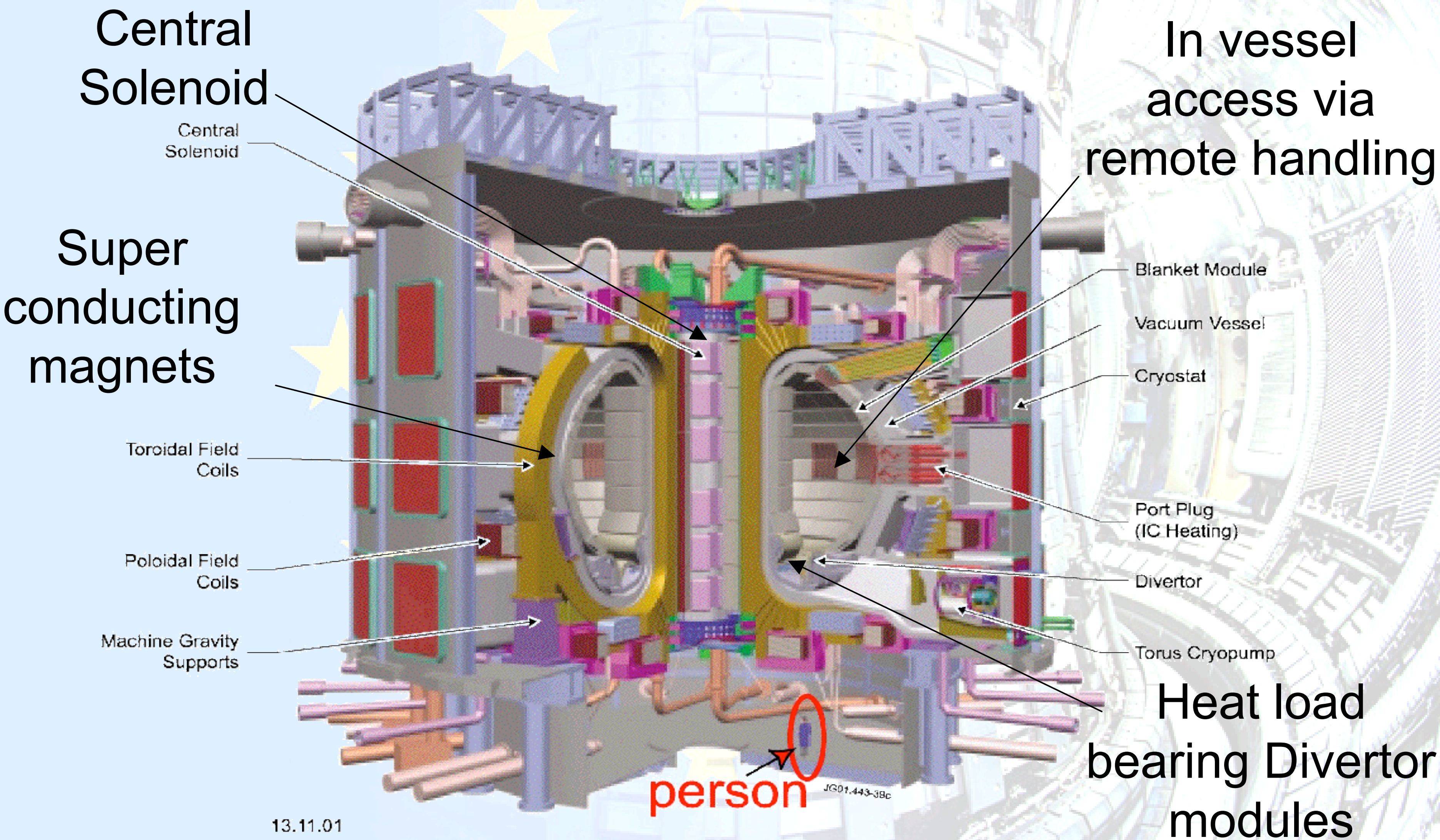
ITER : Overview of the design



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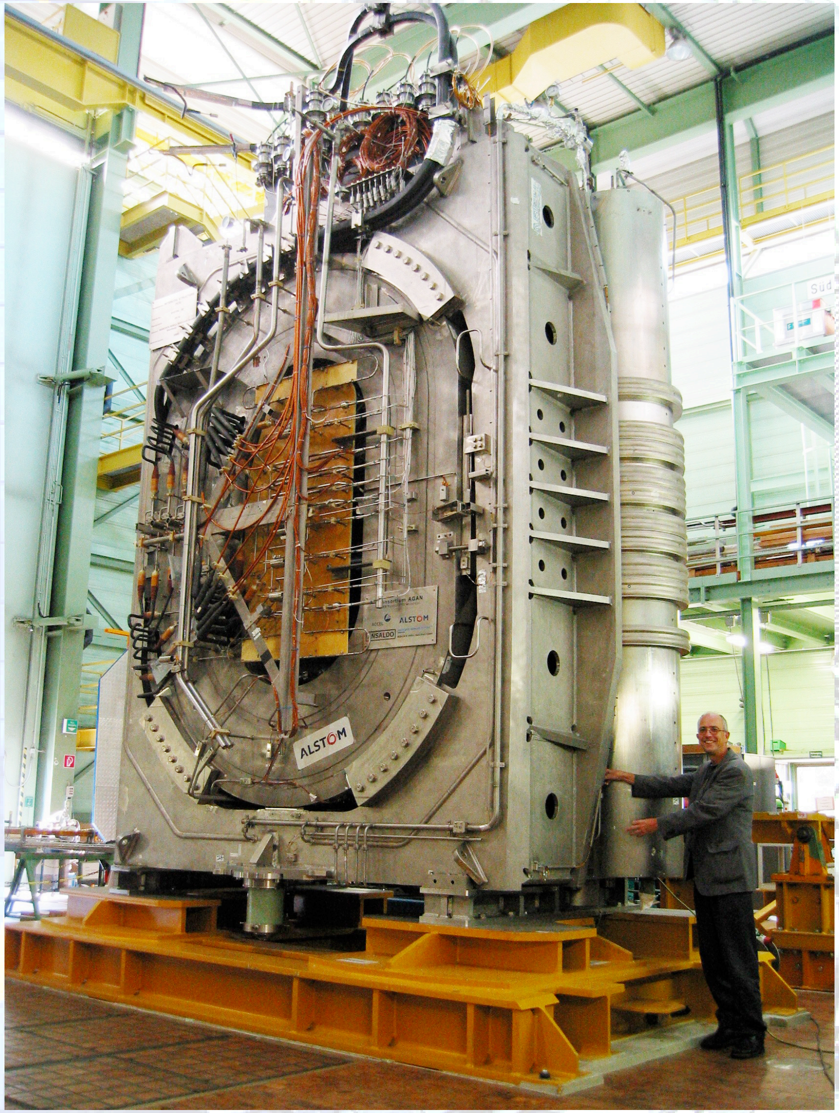
Test of ITER super conducting magnets

ITER Large super-conducting magnets prototypes have been constructed and successfully tested using both Nb_3Sn and NbTi coils

Toroidal Field Model Coil tested in Europe (Nb_3Sn)



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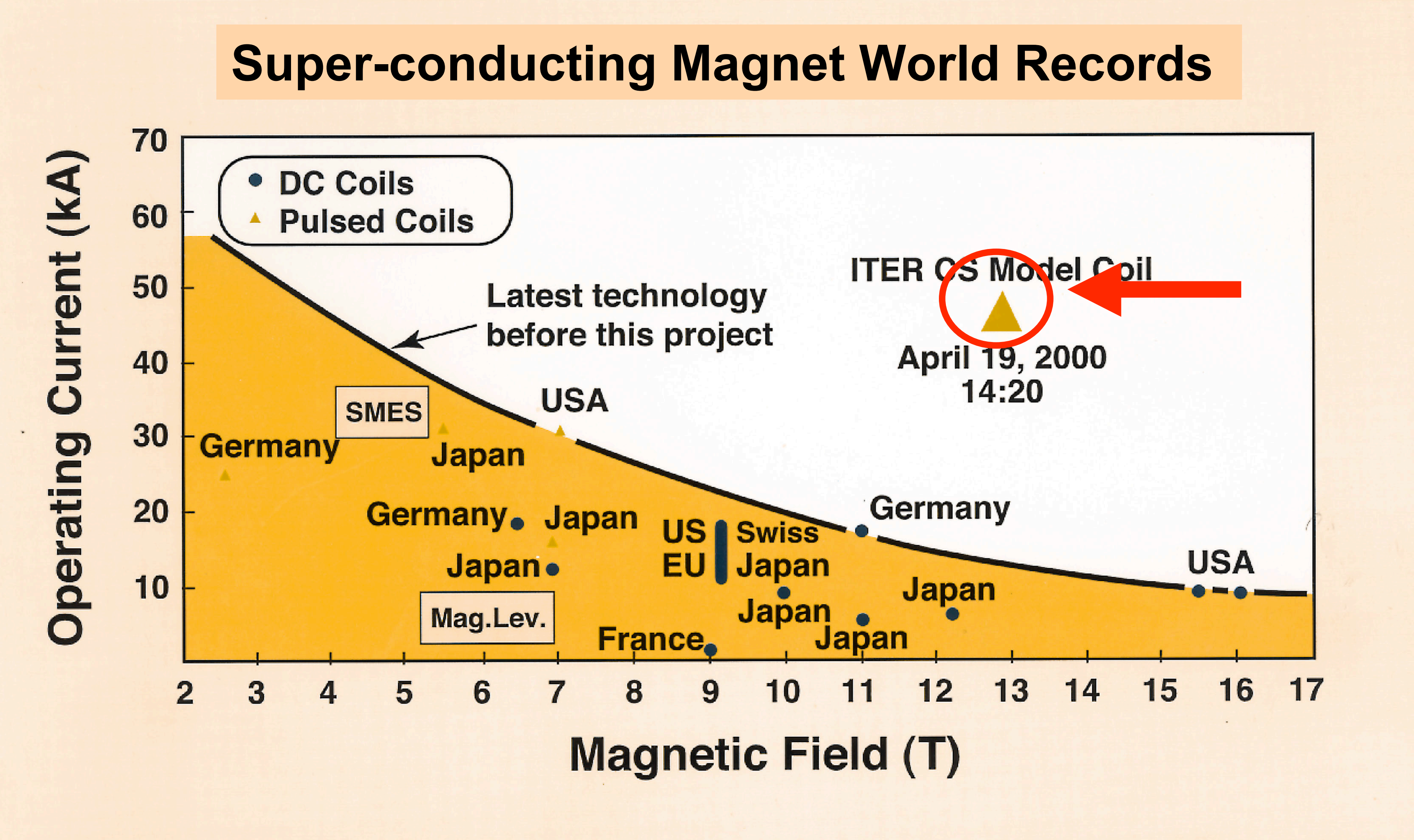
ITER Central Solenoid Demo Coil

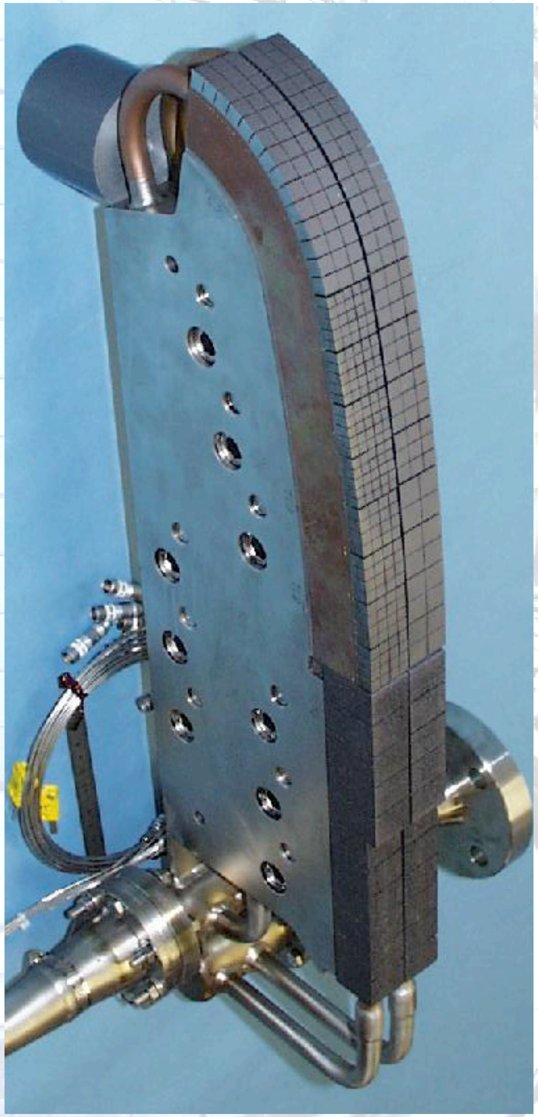


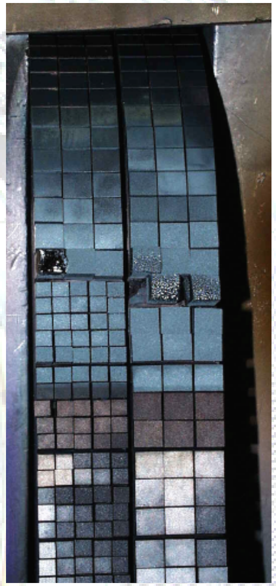
Test of Heat load bearing Divertor modules

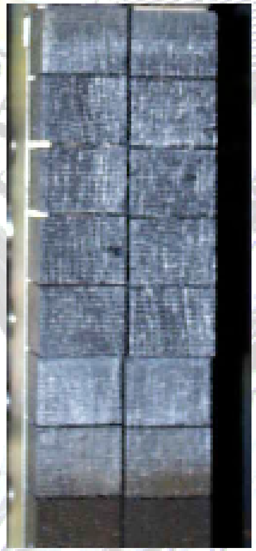
ITER Vertical Target Medium-Scale Prototype constructed and testes successfully

- W macrobrush:
  15 MW/m² x 1000 cycles
- CFC monoblock
  20 MW/m² x 2000 cycles
- CHF test > **30 MW/m²**

Divertor module







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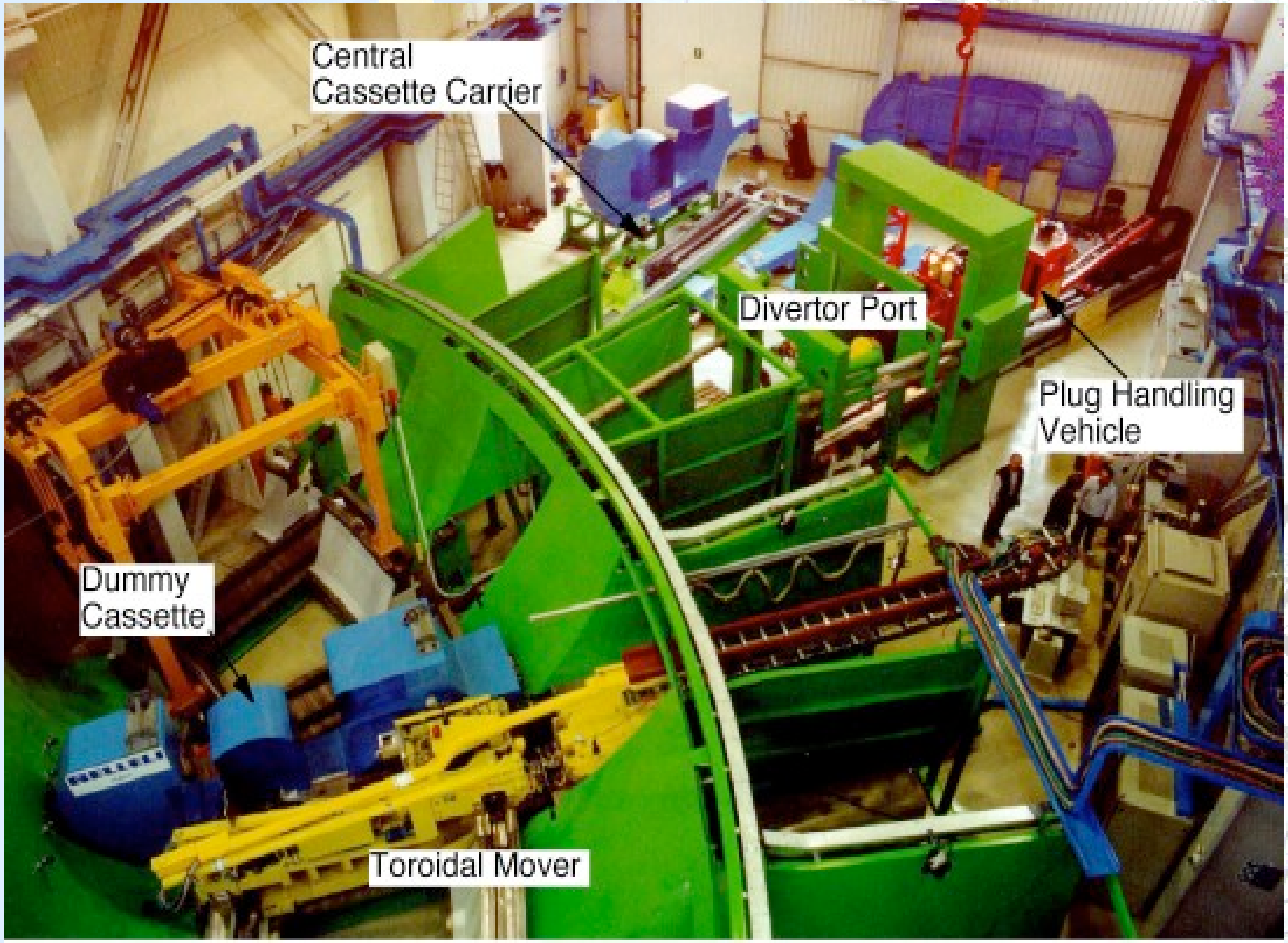
ITER Remote Handling test facility (Italy)



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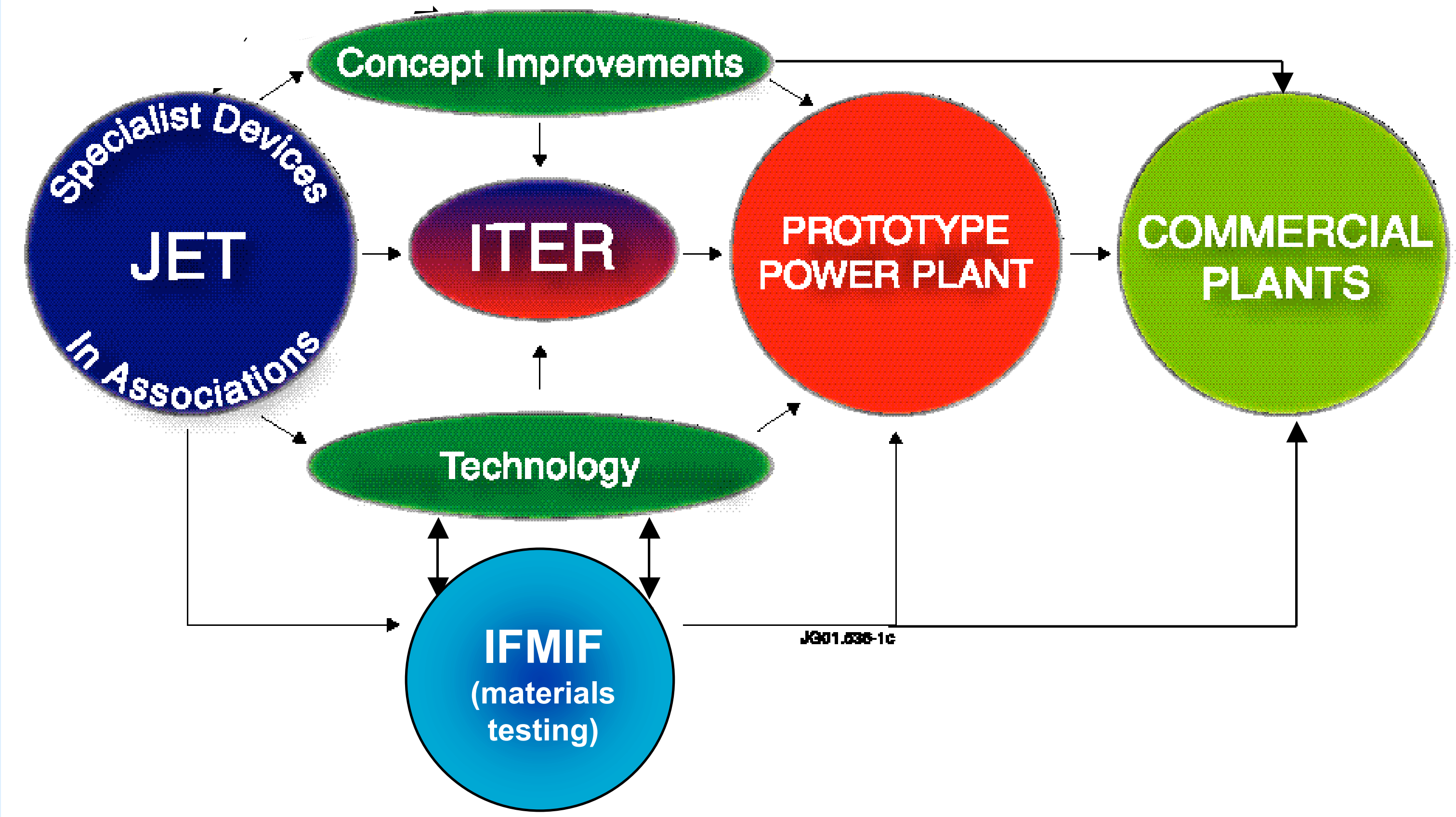
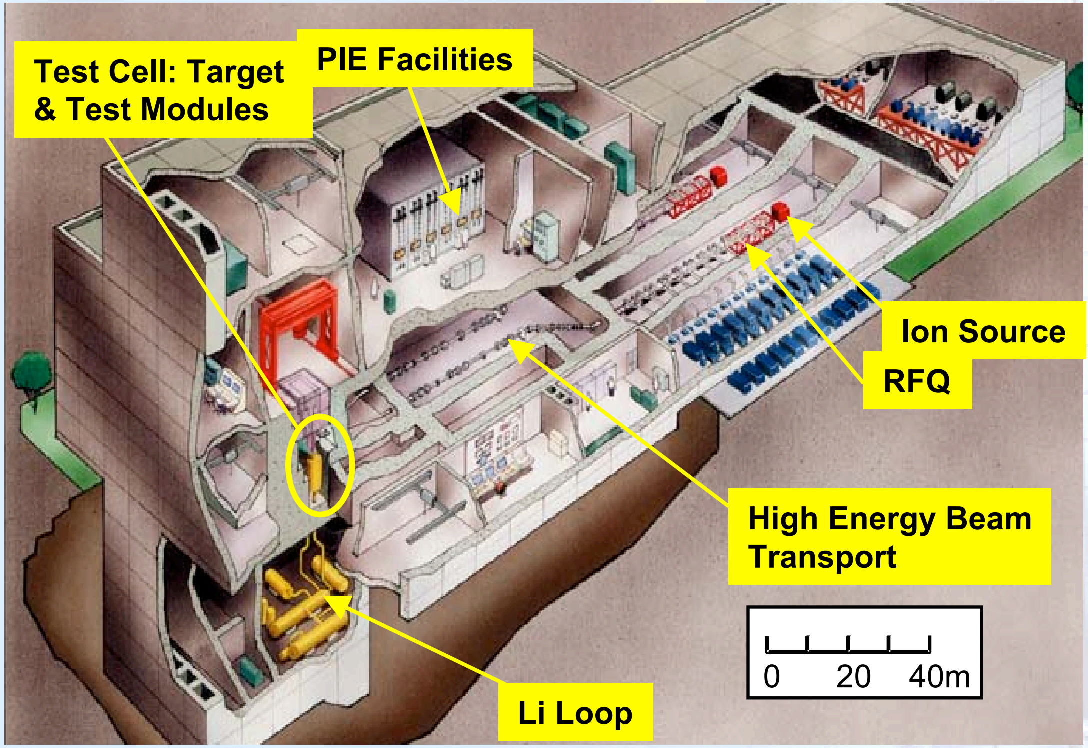
Roadmap to Fusion Power and timescale

Today *Tomorrow (next 2 decades)* *Mid 21st Century*



Proposed: International Fusion Material Irradiation Facility (IFMIF)



IFMIF, jointly planned by Japan, the European Union, the United States and the Russian Federation under the direction of the IEA (International Energy Agency), is an accelerator-based deuteron-lithium (d-Li) **neutron source for producing an intense high energy neutrons**

Sufficient irradiation volume for enable **realistic testing of candidate materials and components** used for fusion reactors up to about a full lifetime of their anticipated use in demonstration reactor plant for electricity production and beyond.

Three Major Components of IFMIF

Accelerator

Deuteron accelerators:

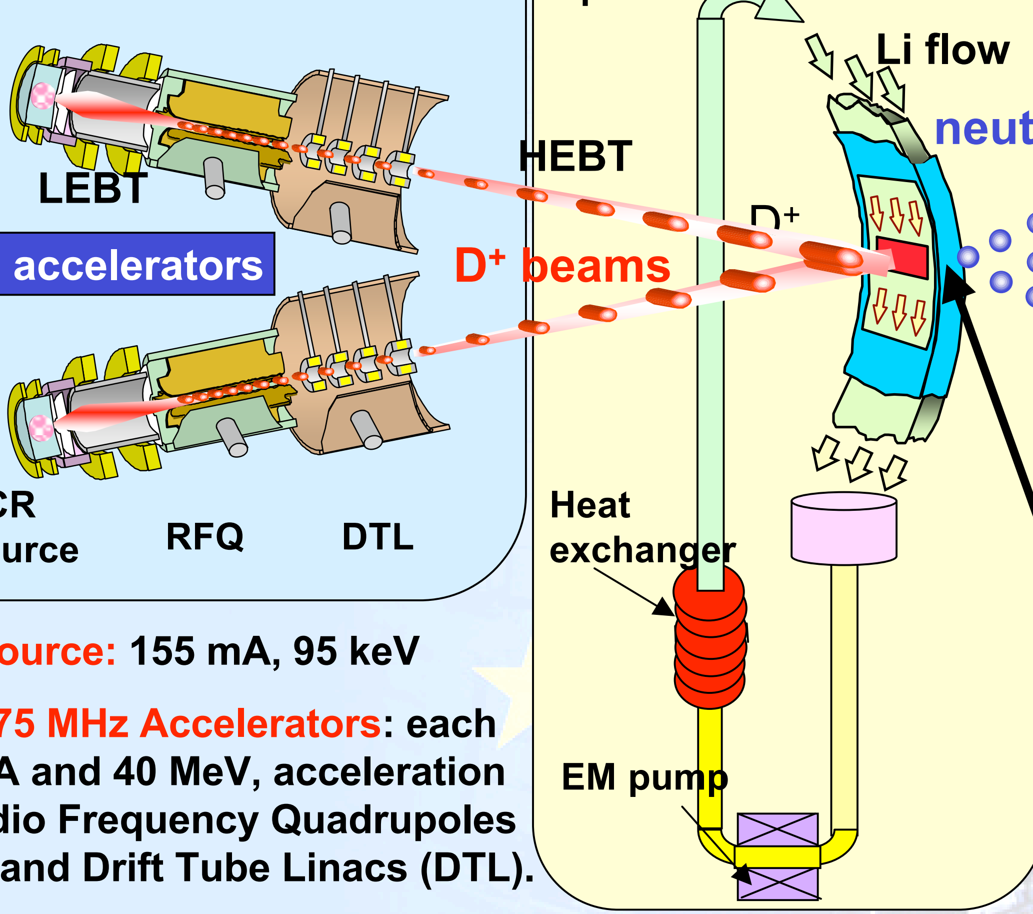
40 MeV 250 mA (10 MW)

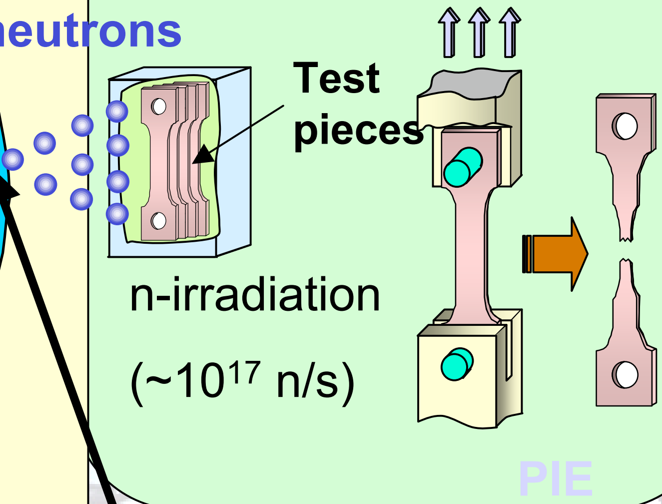
Li Target

- 10 MW beam heat removal with high speed liquid Li flow.

Test Cell

- Irrad. Volume > 0.5L
  for 10^{14} n/(s·cm²), (20 dpa/year)
- Temp.: 250<T<1000℃





ECR source: 155 mA, 95 keV

Two 175 MHz Accelerators: each 125 mA and 40 MeV, acceleration by Radio Frequency Quadrupoles (RFQ) and Drift Tube Linacs (DTL).

Typical reactions:

^{7}Li(d,2n)^{7}Be, ^{6}Li(d,n)^{7}Be, ^{6}Li(n,T)^{4}He.

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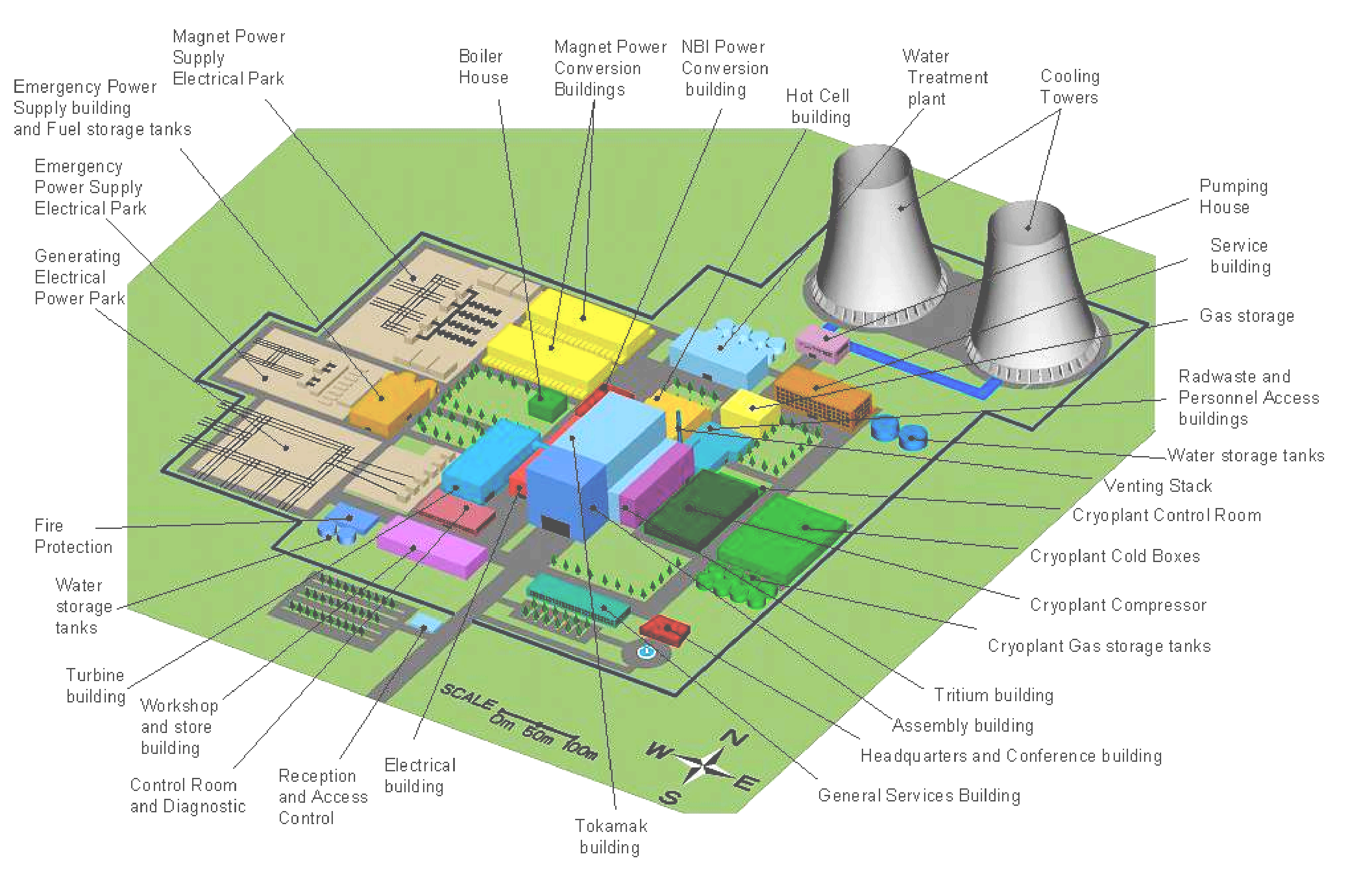
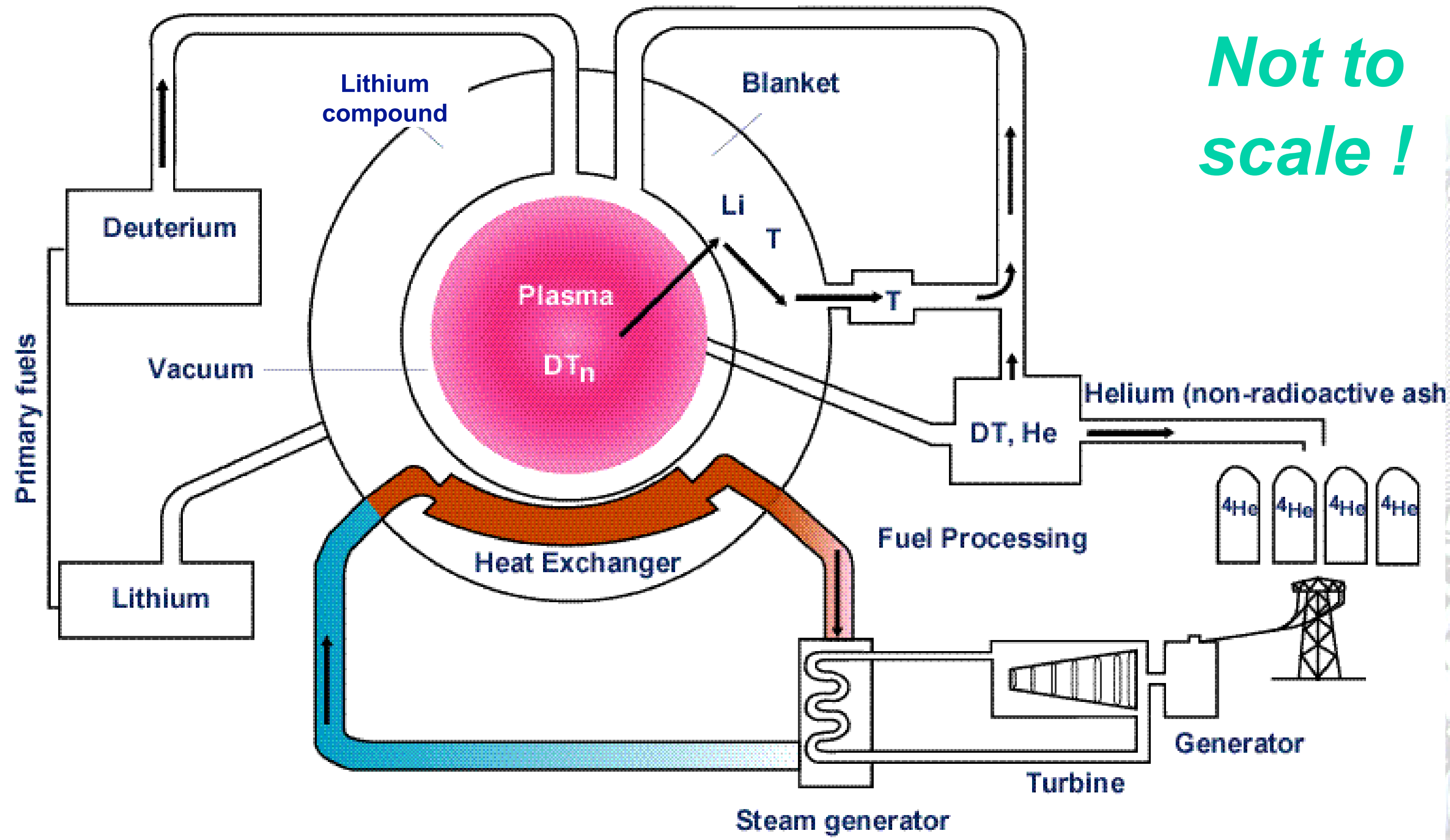
Layout of Conceptual Power Plant



Expected to be similar in size to conventional power plants

A Fusion power plant would be like a conventional one, but with different fuel and furnace



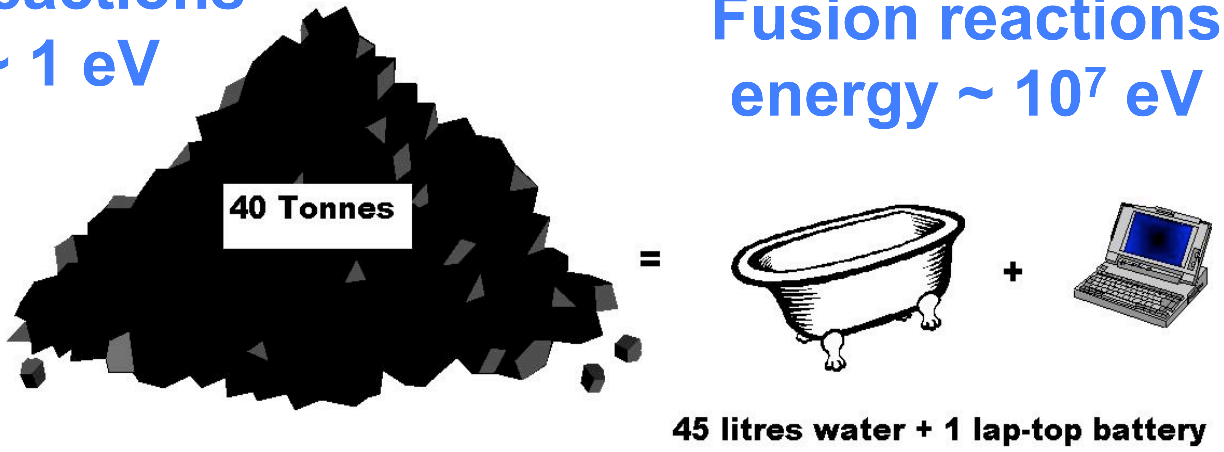
Fuel cycle integrated in plant:
D and Li as basic fuel, T bred in-plant by neutron-Li reactions

Fusion Fuel

- Raw fuel of a fusion reactor is water and lithium (to produce Tritium)

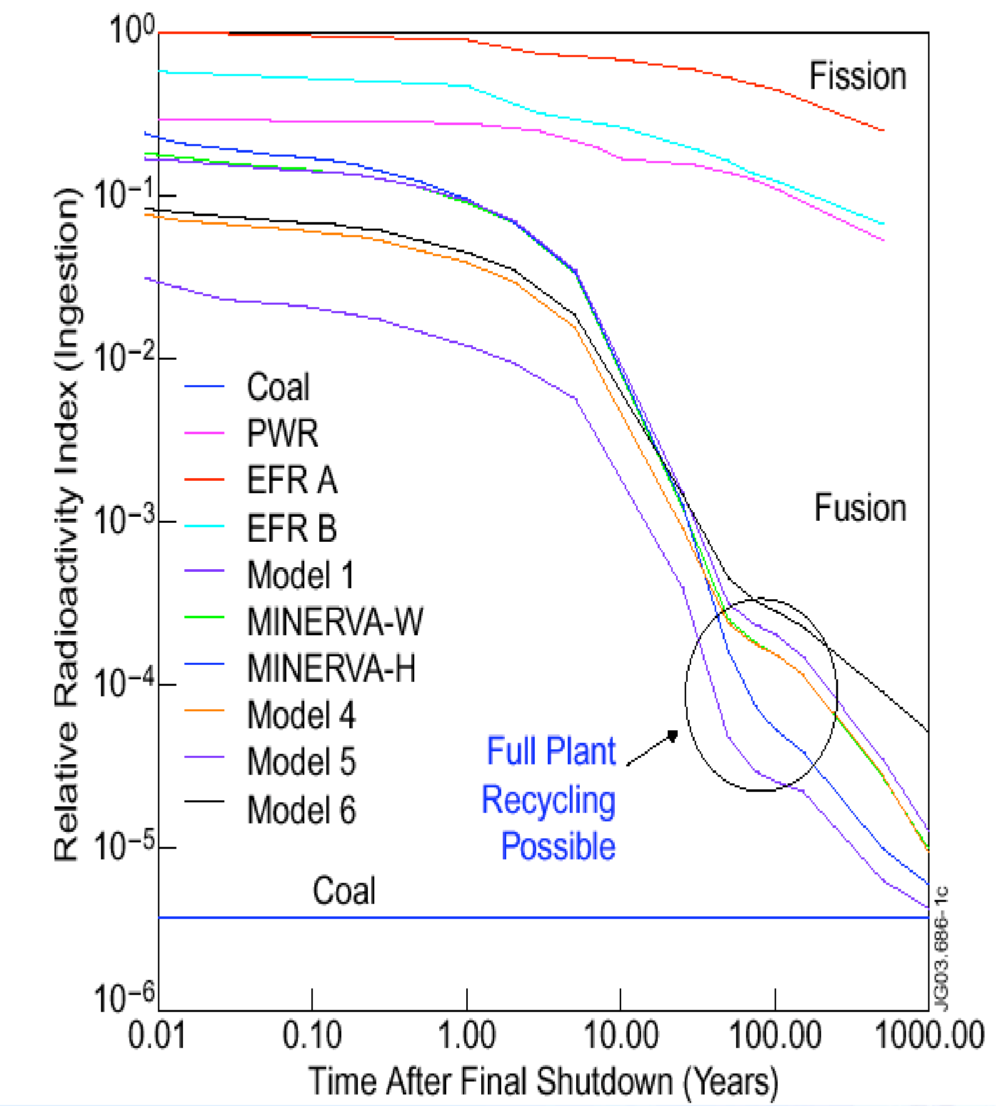
Chemical reactions energy ~ 1 eV

Fusion reactions energy ~ 10^7 eV



- Lithium in one laptop battery + half a bath-full of water 200,000 kW-hours
- ~ 30 years of electricity for a European citizen

Avoiding long-lifetime waste



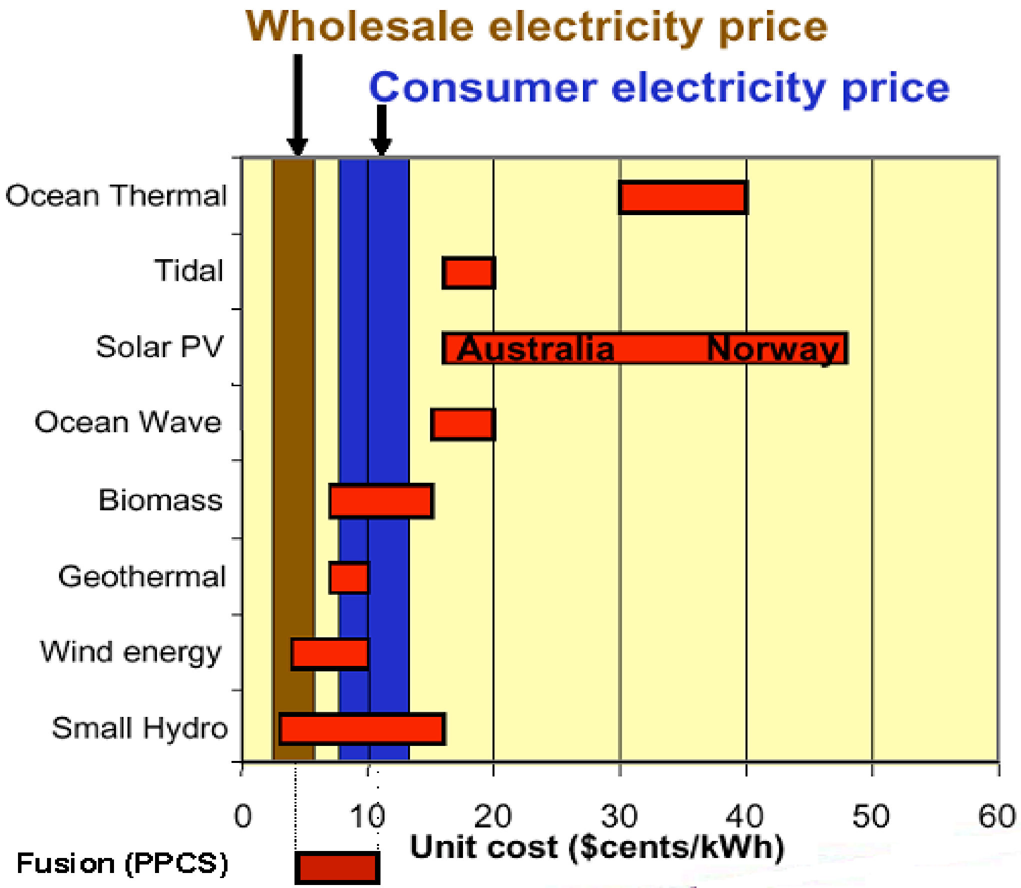
Long term radioactive impact much smaller than Fission and comparable to Coal plants

Short life radioactivity (associated with plant activation)

Fuel cycle inside the reactor, no need for transport of activated materials

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Estimates of Electricity costs from Fusion



An ITER-based Fusion Power Plant Would Produce Electricity at less than Solar (PV) and around Wind Power Costs

For fusion the range is from the ITER operating point up to β_N=3.4

Summary

Few options exist for large scale energy production in the second half of XXI century:

Nuclear Fission Long term storage of high level radioactive waste

Fossil fuels (Coal) Green house gas emissions and global warming

Renewables cannot provide a solution for the global energy problem

We need a further option:

Nuclear Fusion Safe & low level radioactive waste, no atmospheric pollution

Summary

- 22 MJ of fusion Energy **4.5 MW Steady state Fusion Power** (**16 MW Fusion peak power**) achieved in JET deuterium tritium experiments in 1997 and demonstrated alpha heating
- With **Q > 10**, ITER would provide access to plasmas with adequate self heating ($f\alpha$ > 2/3), **burning fusion plasma** and Test essential technologies in reactor-relevant conditions
- Main ITER components successfully tested, **super-conducting magnets**, **Heat load bearing divertor modules** and **Remote Handling test facility** and it is **ready to be built**.
- In parallel, IFMIF neutron source for producing an intense high energy neutrons would **enable realistic testing of candidate materials and components** used for fusion reactors.
- Long term radioactive impact much smaller than Fission and comparable to Coal plants
- An ITER-based Fusion Power Plant would produce electricity at less than Solar (PV in UK), and around Wind Power Costs