IAEA Artsimovich Memorial Lecture

René PELLAT

① Energy consumption and needs

② Magnetic confinement

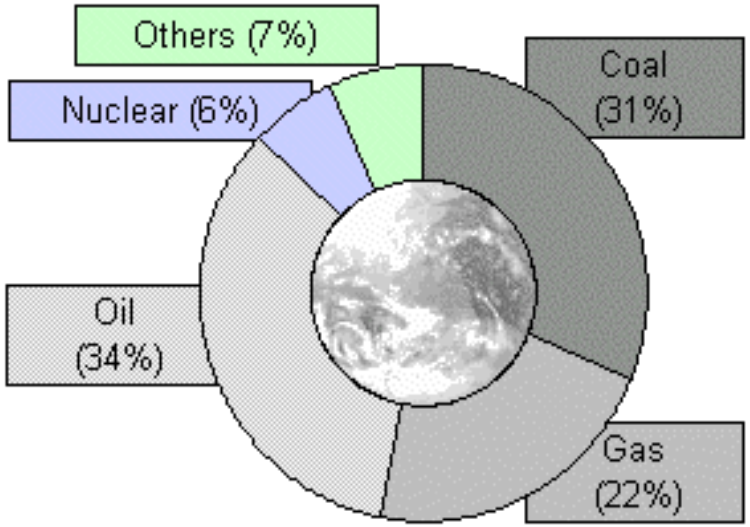
- Tokamaks
- Stellarators

③ Inertial confinement

④ The road towards the reactor : ITER

① ENERGY CONSUMPTION AND NEEDS

Energy Consumption and Resources



⇐ Present repartition of consumption (primary energy).

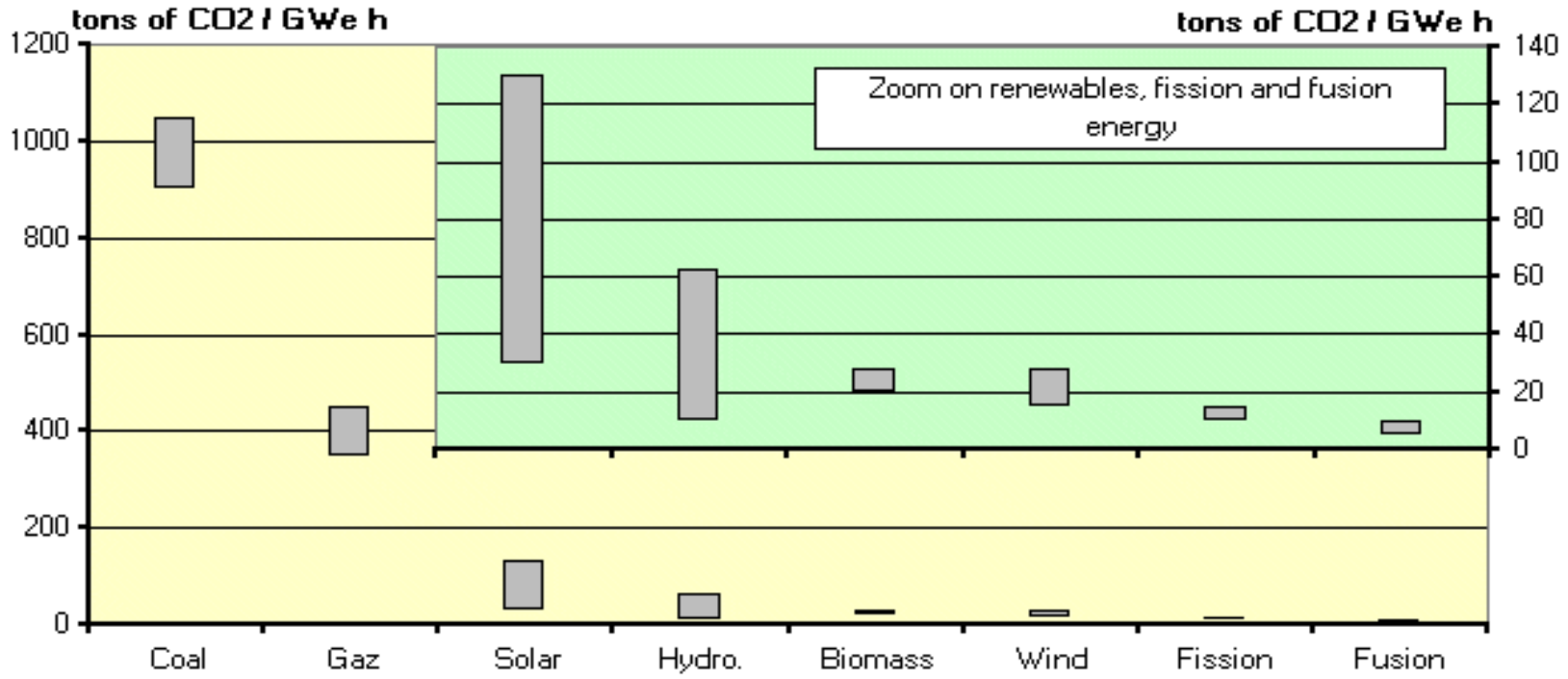
- Fossil fuels cover ≈ 85 % of primary energy needs.
- Fuel reserves rapidly decreasing.

⇓

Fuel	Energy value	toe	Proved reserves	Years of use at current rate
Crude oil	1 ton=42 GJ	1	9.5 10^{11} barrel	40 - 50
Coal	1 ton=29.3 GJ	0.69	10^{12} ton	220
Natural gas	10^3 m^3=36 GJ	0.86	1.2 10^{14} m^3	60 -70
Uranium	1 ton=4.2 10^5 GJ	10^4	2 10^6 ton	40 – 50 (breeder ≈ 3000)

The Greenhouse Effect

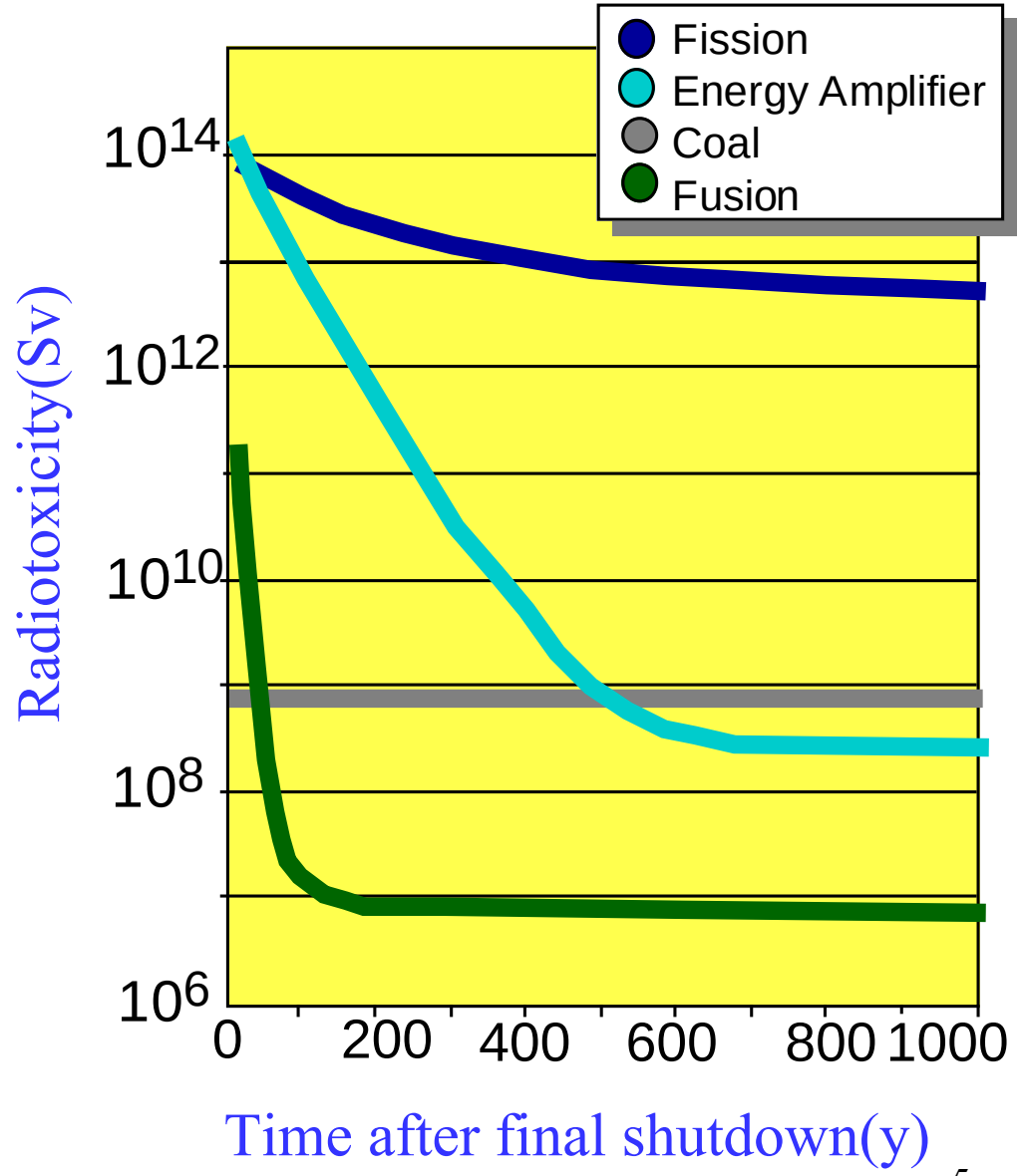
- Limited fossil resources.
- CO_2 release (>10^{10} ton/year in the atmosphere) → greenhouse effect. Average temperature increase ; climate affected.
- CO_2 removal takes more than 100 years, through slow carbon exchange between surface water and deep ocean.



Radiotoxicity

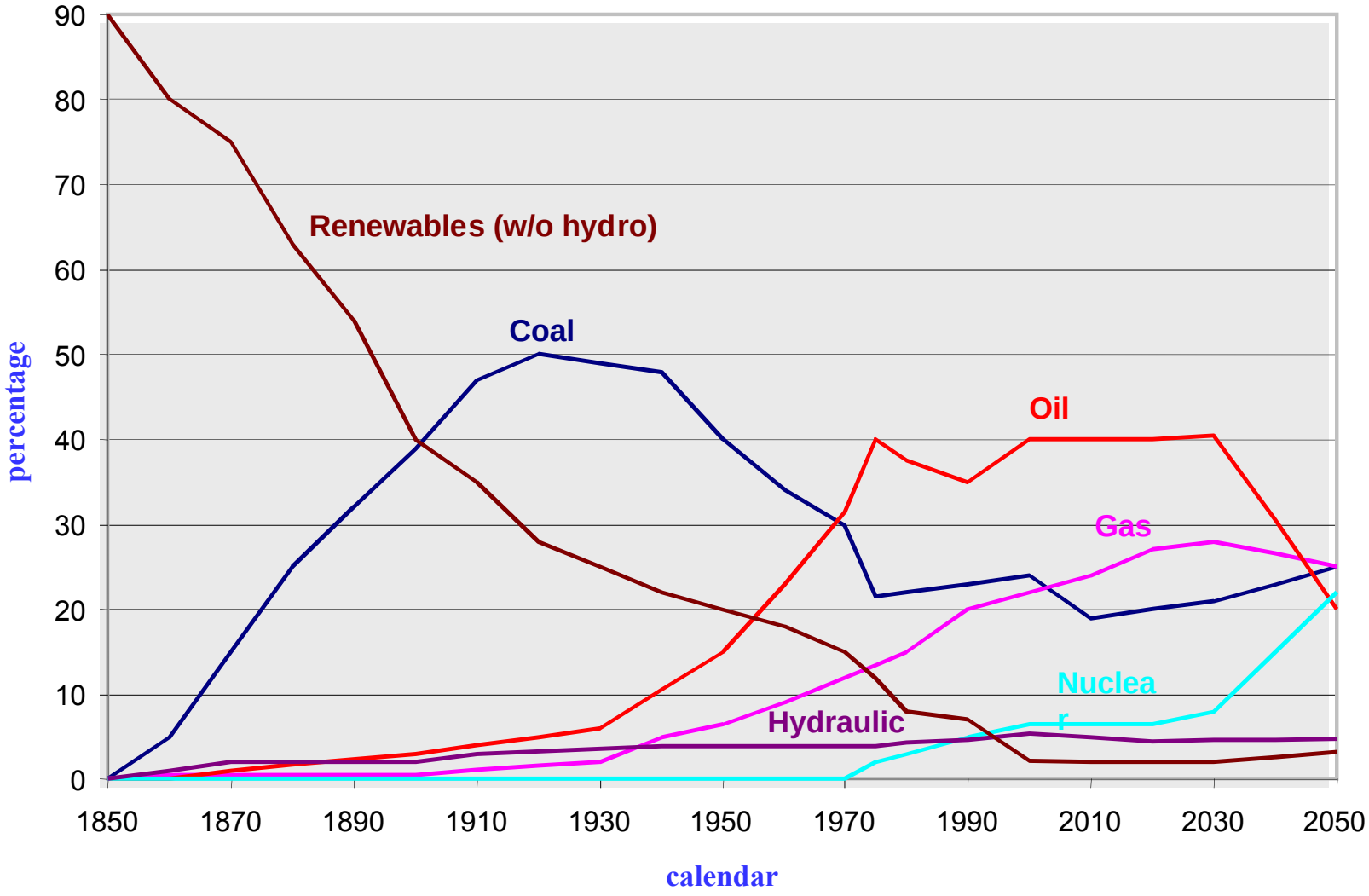
for the same total electrical energy generation

- Fission
  without reprocessing
- Energy amplifier
- Coal-fired plant
- Fusion



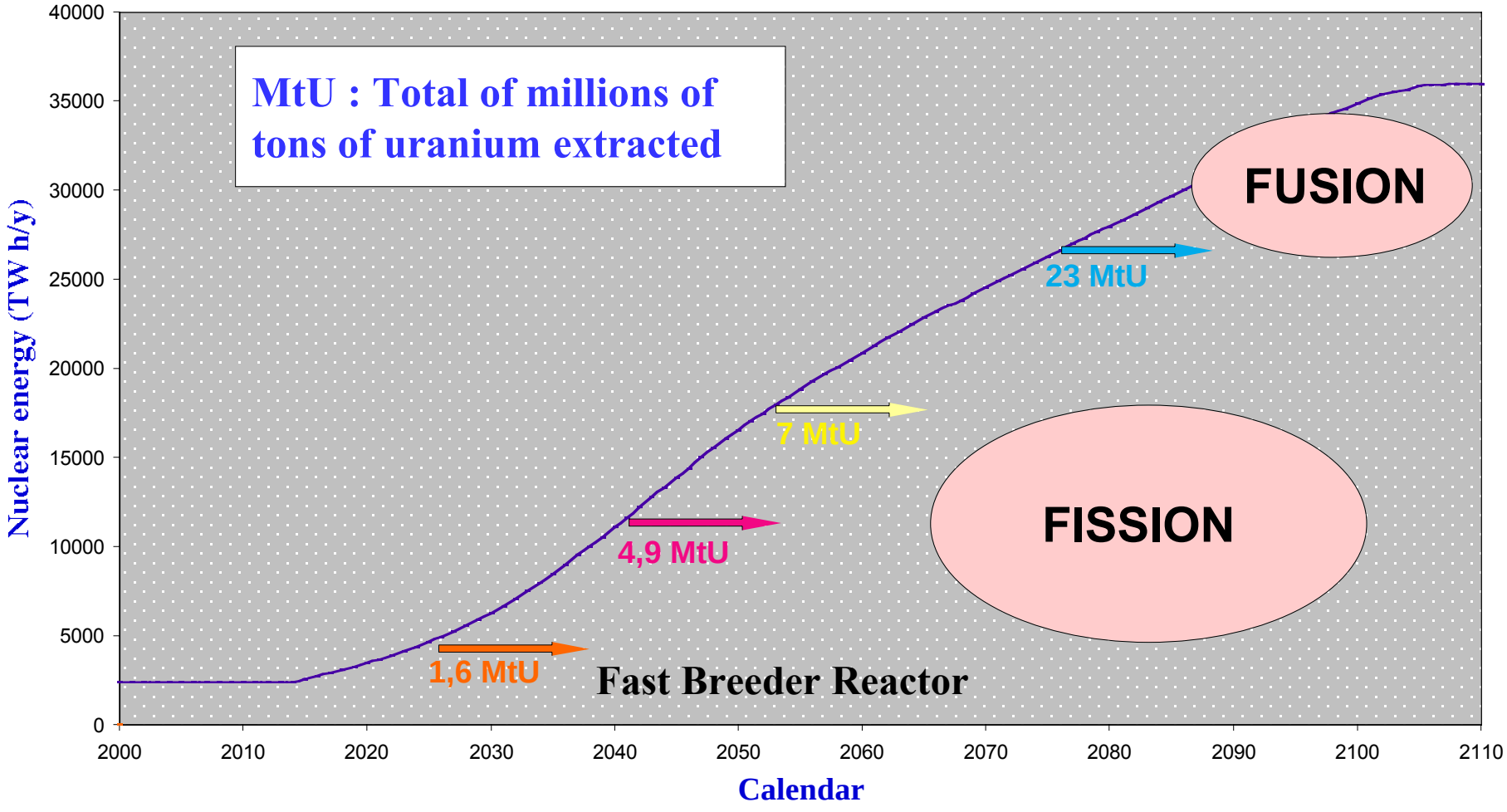
Source : P. Magaud

World Primary Energies 1850-2050



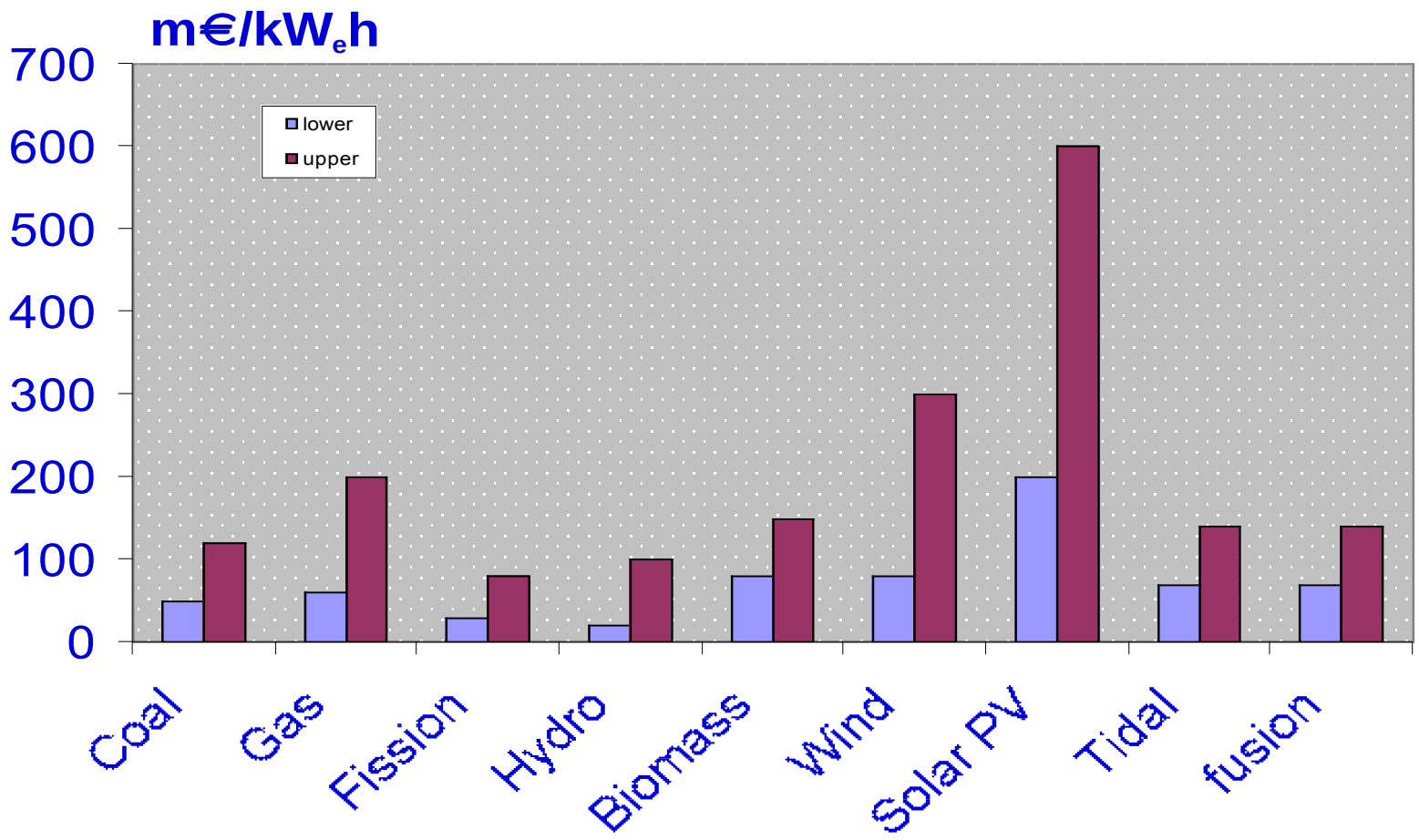
Source : R.T. Bauquis, A. Simon

Nuclear Energy Contribution to Future World Needs
Complementary fission and fusion



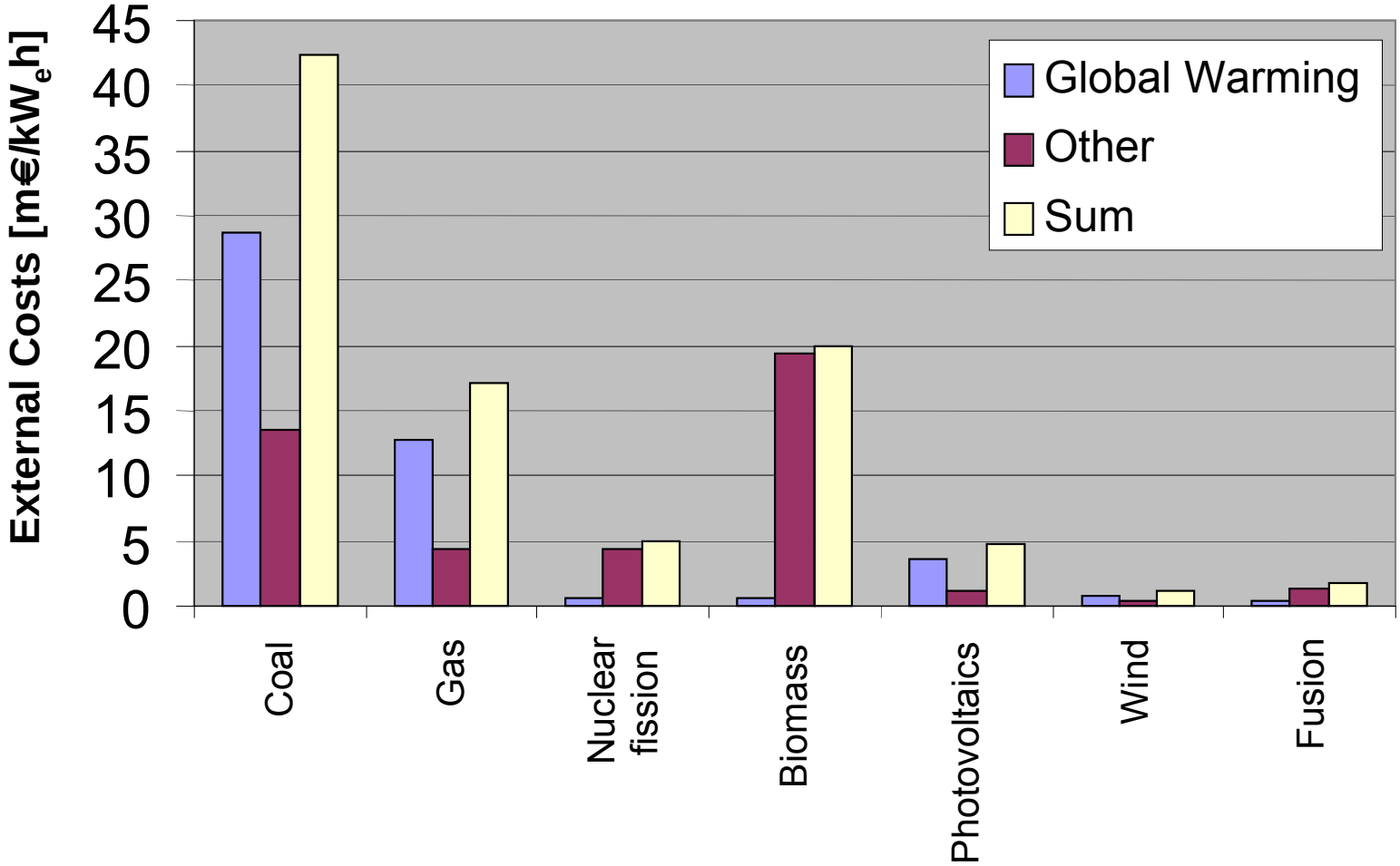
Source : A. Simon

Uncertainties in Projected Direct Costs of non-intermittent power



Source : S. Paidassi

External Costs



Source : S. Paidassi

Thermonuclear Fusion

$$D + T \rightarrow {}^{4}He\ (3.5\ MeV) + n\ (14.1\ MeV)$$

$${}^{6}Li + n \rightarrow {}^{4}He\ (2.05\ MeV) + T\ (2.73\ MeV)$$

$$D + {}^{6}Li \rightarrow 2\ {}^{4}He + energy$$

Resources for more than 10^6 years : limited by lithium.

With the D-D reaction, resources for more than 10^{10} years.

Main avenues of research :

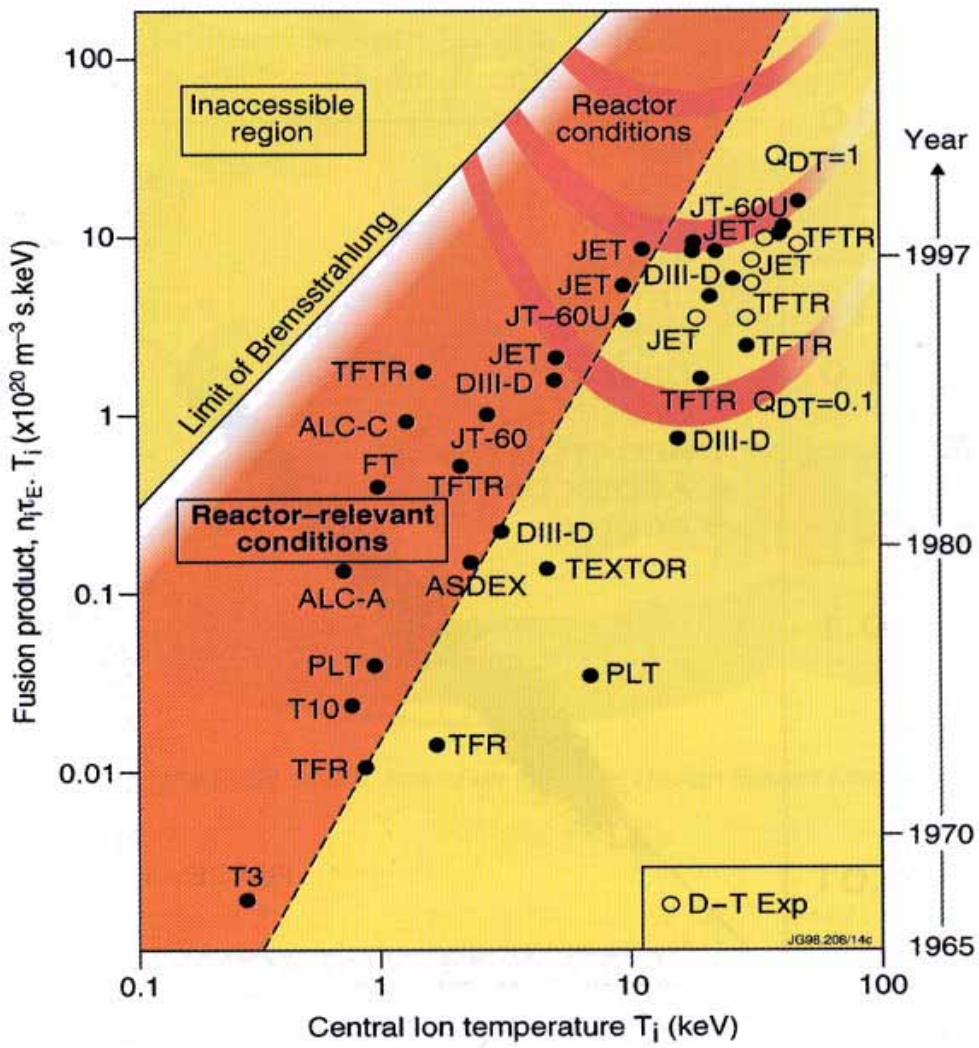
Magnetic confinement : tokamaks, stellarators.

Inertial confinement : lasers, ion accelerators.

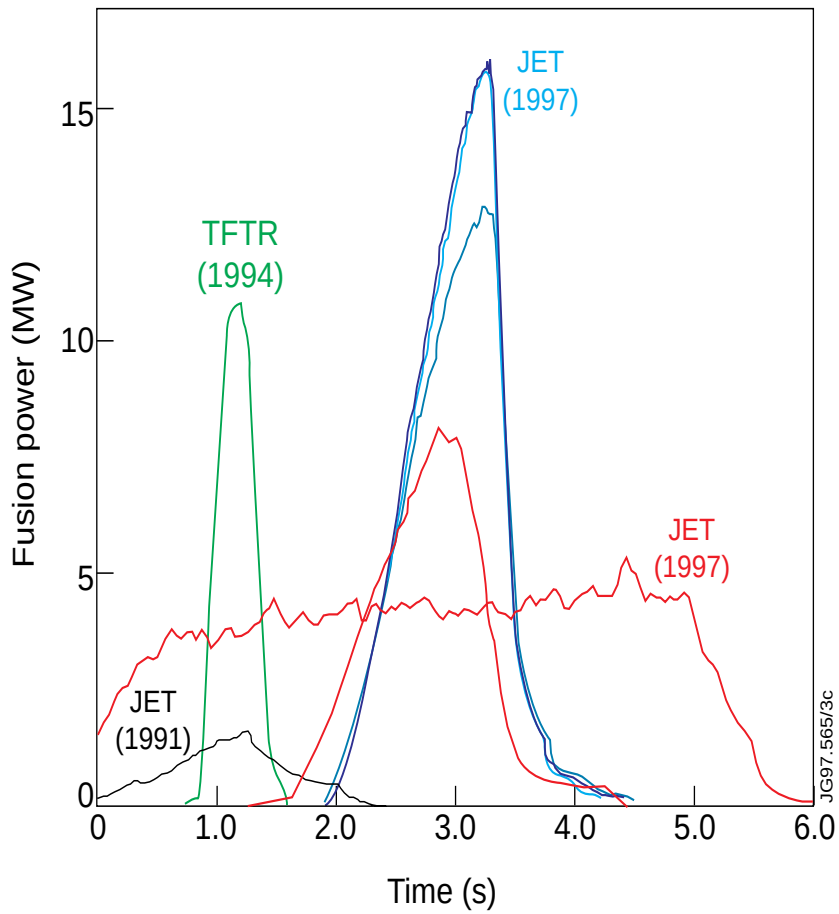
② MAGNETIC CONFINEMENT

Tokamaks

Progress over the last thirty years



D-T Experiments



- Q = 0.7, transient regime.
- 22 MJ in quasi steady-state ELMy H-mode.
- Evidence of α-particle heating.
- Lower H-mode threshold.
- Optimised shear with bootstrap current and current drive.
- ICRF heating in ITER-relevant conditions.
- Tritium and remote handling.

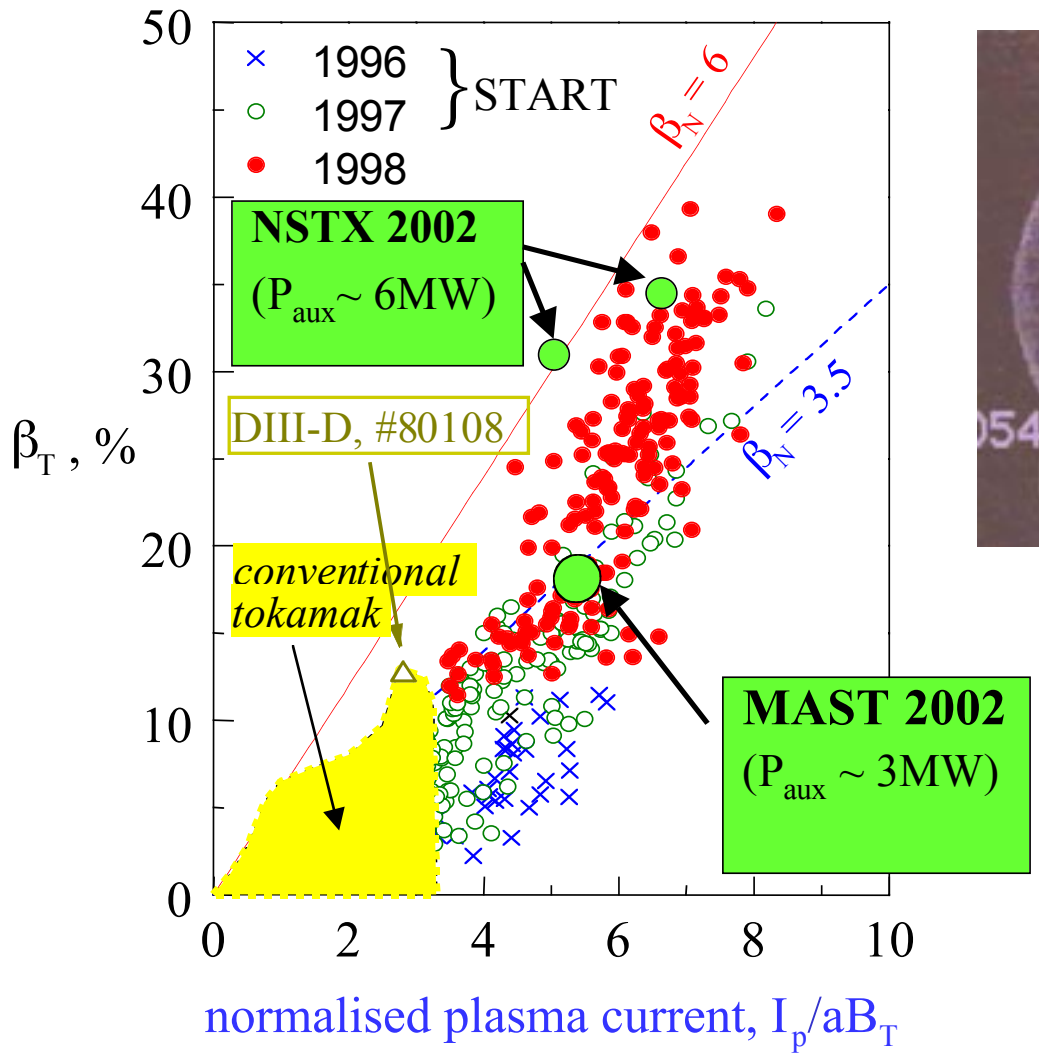
Plasma Stability

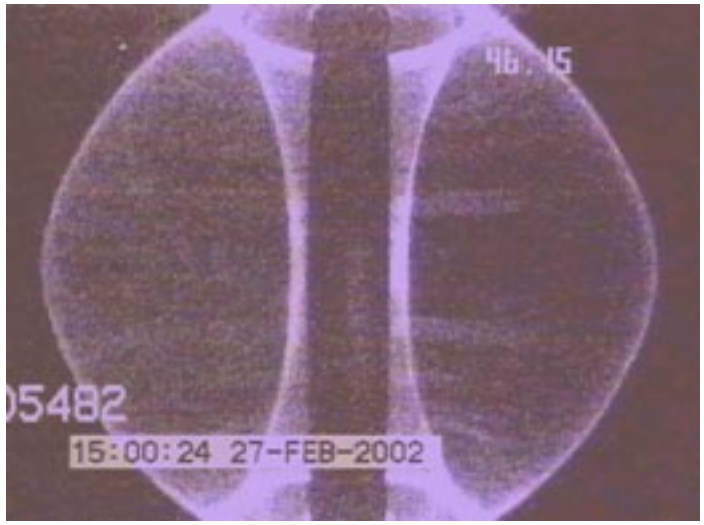
- Reliable codes exist to predict large scale stability :
  - Operational limits : β, disruptions.
  - Neo-classical tearing mode development.
  - α-particle instabilities.

- Anomalous transport due to small scale instabilities is better understood :
  - Extrapolation to ITER relies on wind tunnel approach.
  - Gyro kinetic theory is progressing : numerical simulation shows onset of internal transport barrier due to shear flows.

Spherical Tokamak raises β_N and β_T

START results are being verified in NSTX and MAST 2nd generation



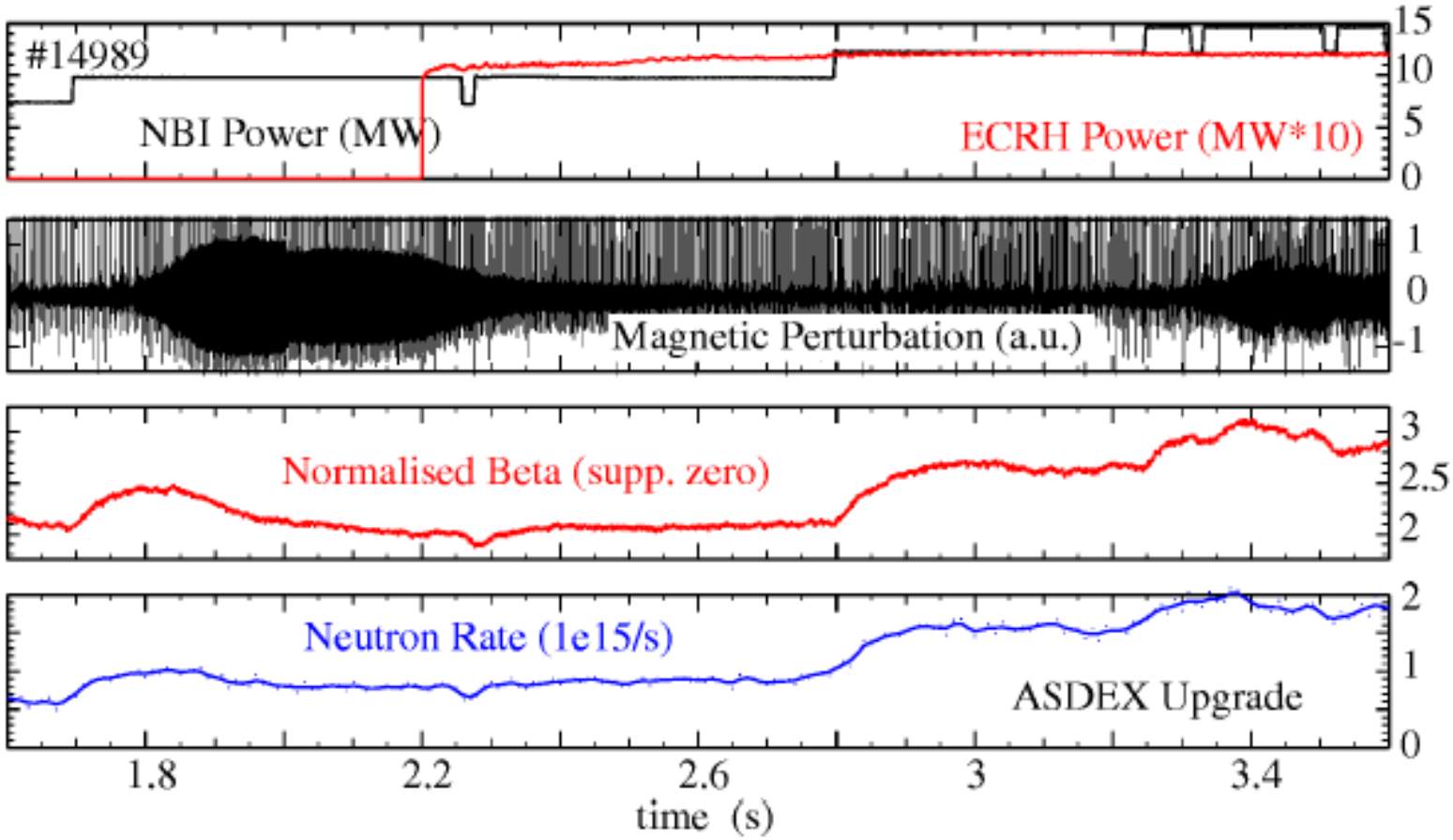


MAST H-mode discharge

Source : A. Sykes

Example of MHD Control
Neo-classical tearing mode active ECRH feedback

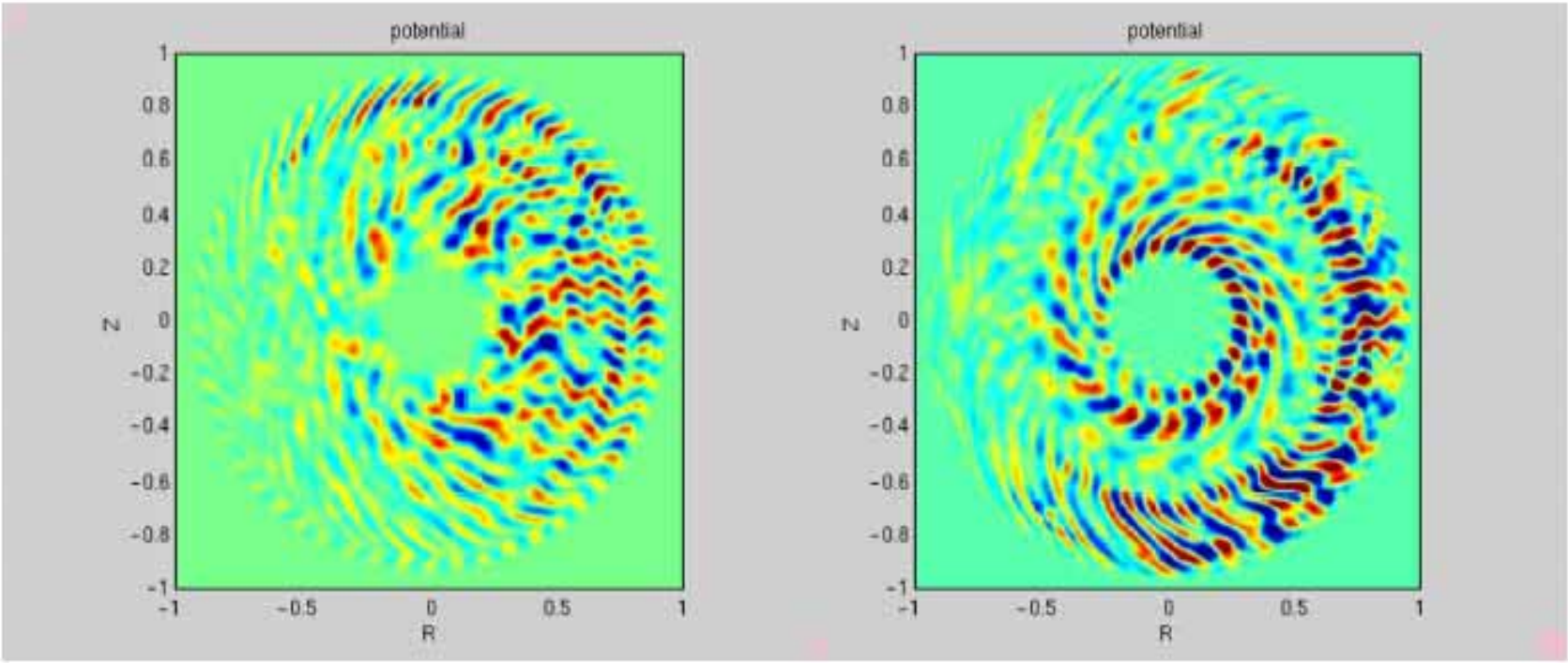
ASDEX Upgrade



Turbulence Simulations of an Internal Transport Barrier

Monotonic q profile

Reversed q profile



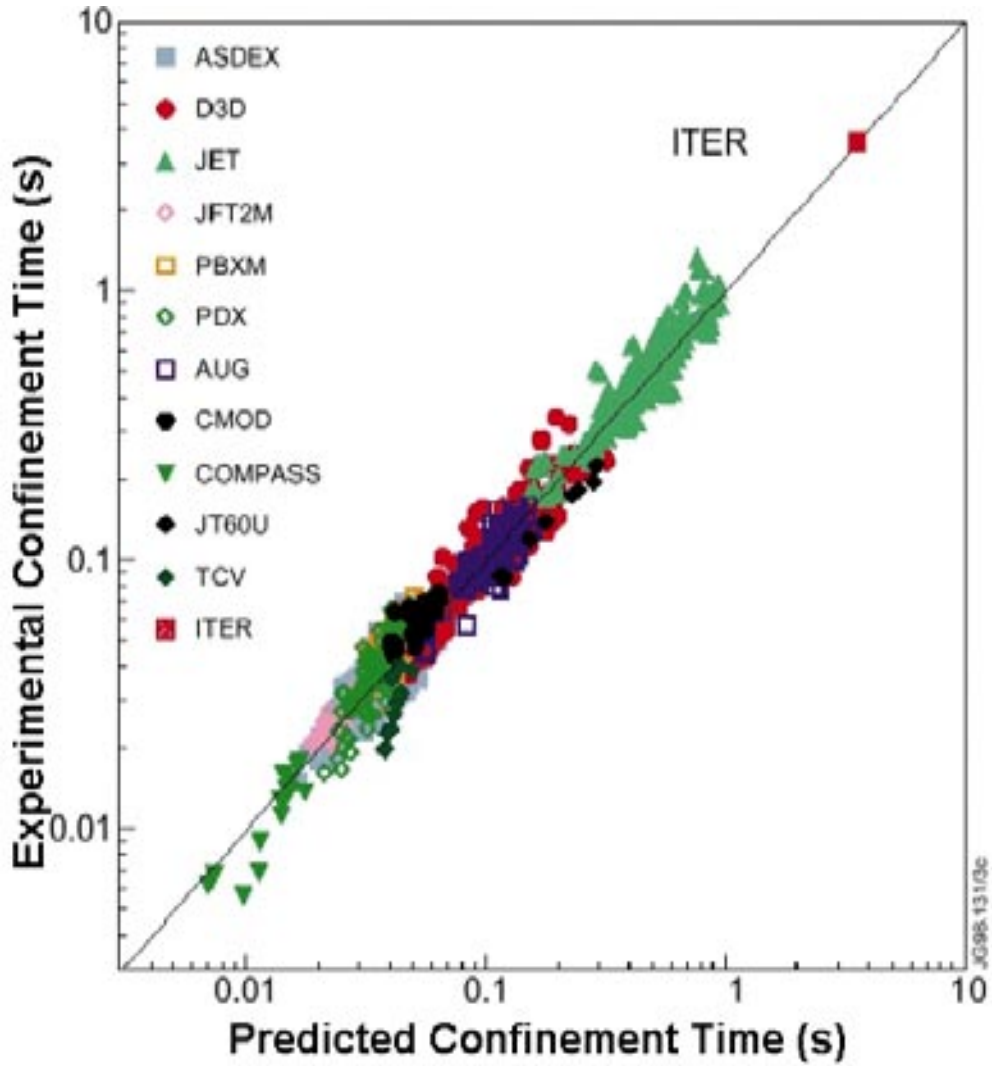
Perturbed electric potential.

Source : X. Garbet

Empirical Prediction of Tokamak Confinement

- Consistent scaling behaviour on many tokamaks, implying common underlying transport physics.
- Multi-machine confinement can be deduced from dimensionless wind tunnel scaling to provide a robust physics basis :

$$\tau_{E,th,ELMy} \propto \rho^{*-0.83}\, \beta^{-0.50}\, \nu^{*-0.10}$$



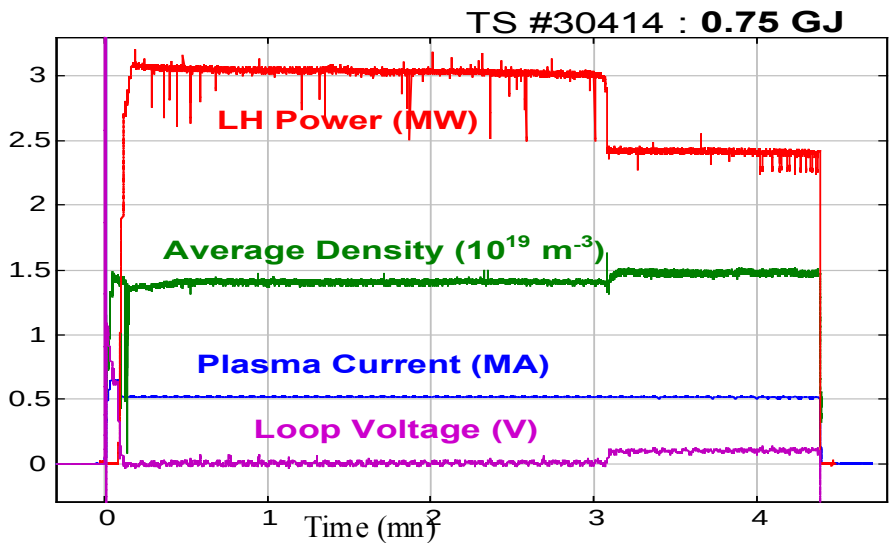
Source : R.D. Stambaugh

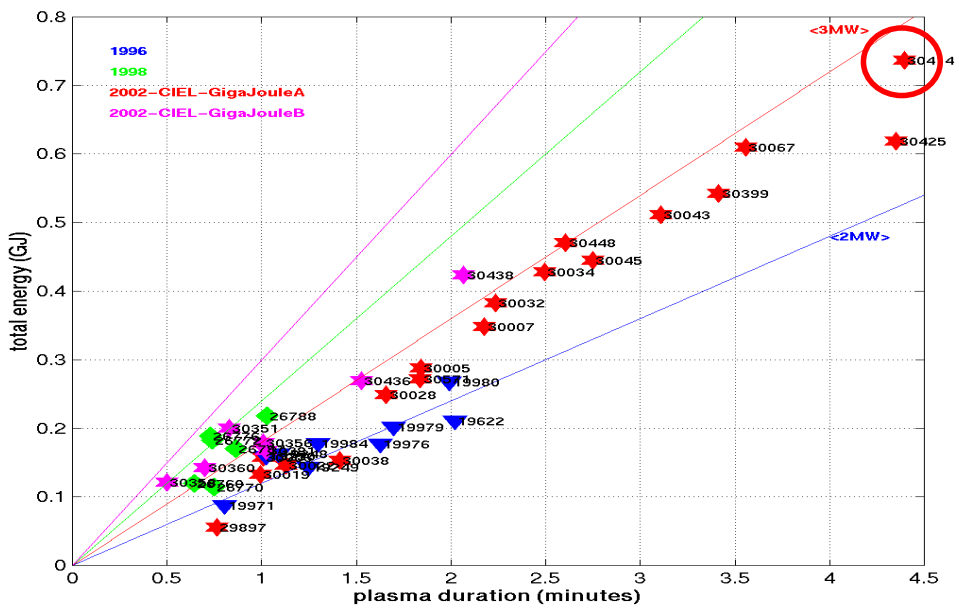
Long Pulse and Steady-State

- Reactor requires hour long operation, creating the need for :
  - Superconducting magnets.
  - Deep fuelling, heating and exhaust with active cooling.
  - Active feed-back for plasma control and optimization.
  - Non-inductive current drive for steady-state tokamak.

- Good progress has been achieved in all these areas, but emphasis has now to be put on industrial realizations of actively cooled components and long pulse heating sources.

Long Duration Discharge on Tore Supra



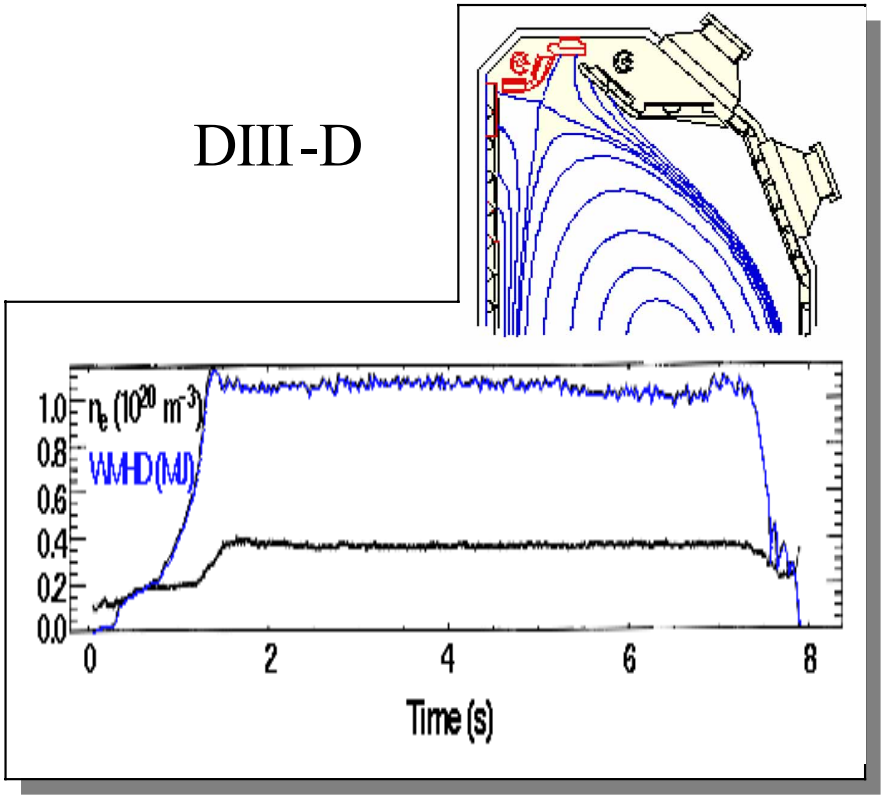


750 MJ injected and extracted : all actively cooled internal plasma facing components (elementary finger : CFC on CuCrZr), limited to 11 MWm^{-2}.

Particle Confinement Time Scale Pumping, a mandatory issue for long pulses.

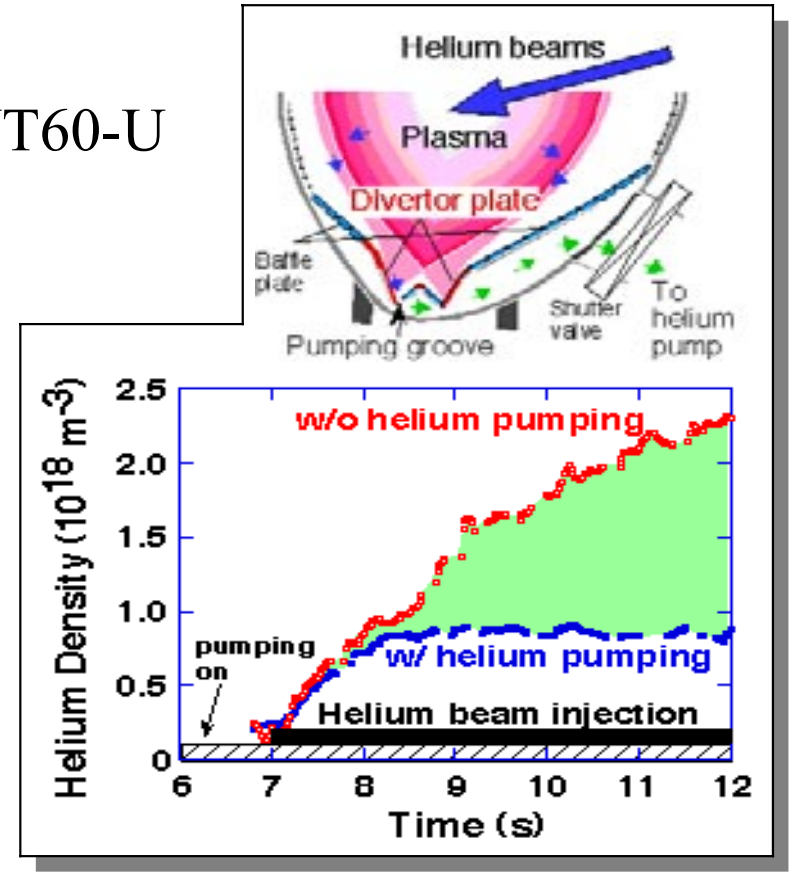
Plasma density regulated by gas fuelling and divertor pumping

DIII-D

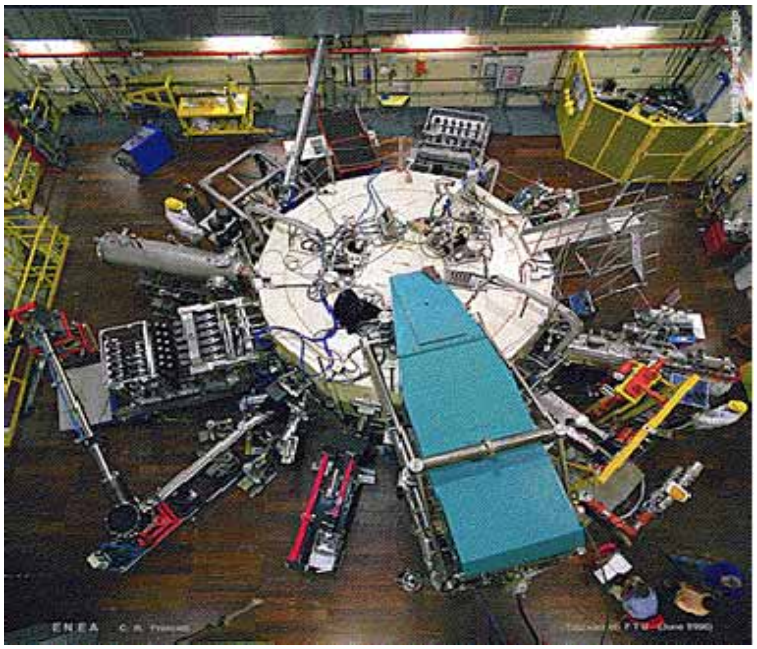


Helium exhaust during an H-mode

JT60-U



Source : B. Saoutic



FTU

(Association Euratom-ENEA, Italy)

high B (≤ 8 T), **high n** (≤ 4 10^{20} m^{-3})

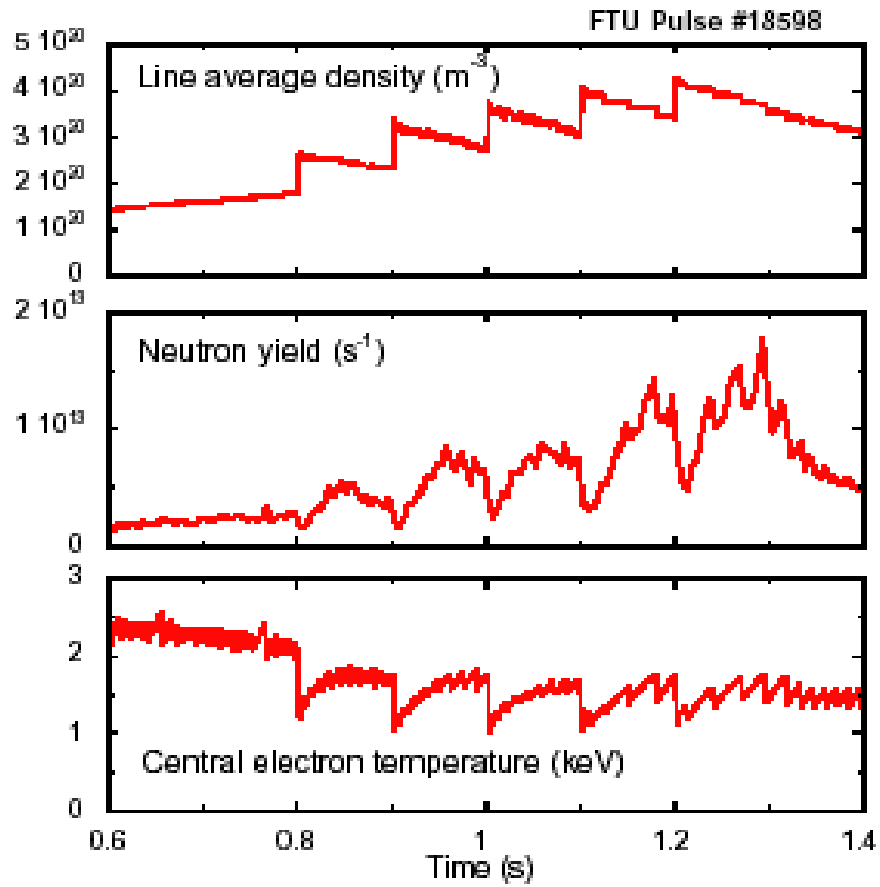
plasmas with RF heating

Enhanced confinement regime with multiple pellet injection

B = 8 T, I_p = 1.25 MA

n_e= 4 10^{20} m^{-3}, H_{89P} = 1.7

$n_{e0}\tau_E T_{i0} = 10^{20} m^{-3} keV\ s$

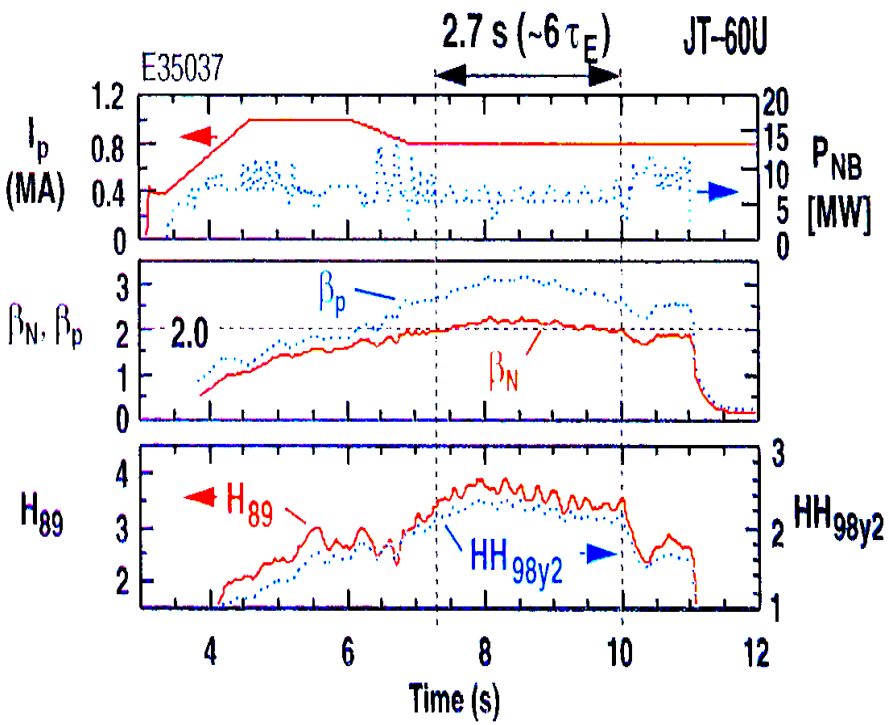


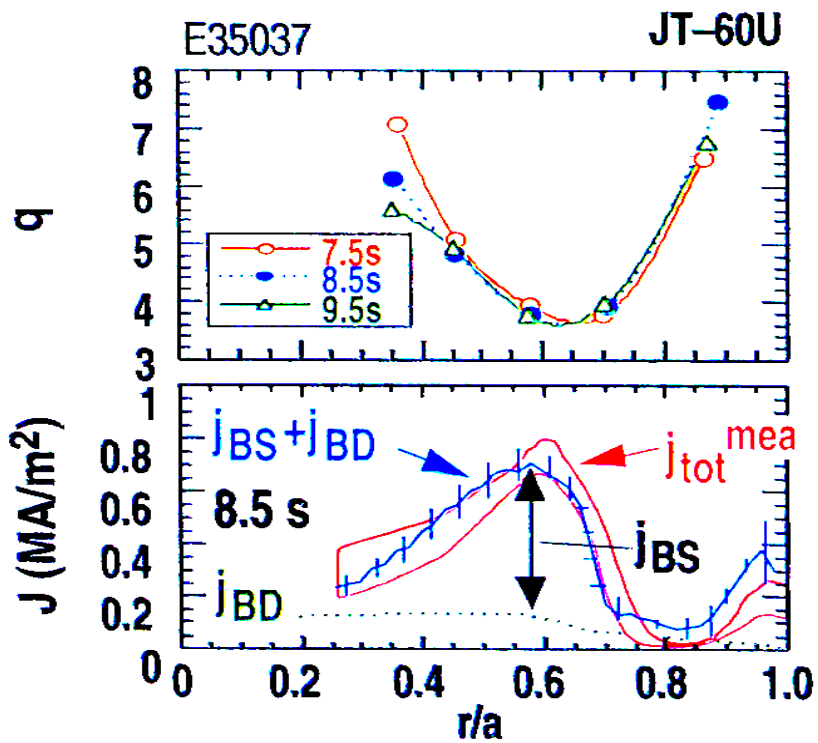
Ref.: Alladio et al., IAEA 2000

Fully Non-Inductive Current Drive

JT-60U (80 % bootstrap)

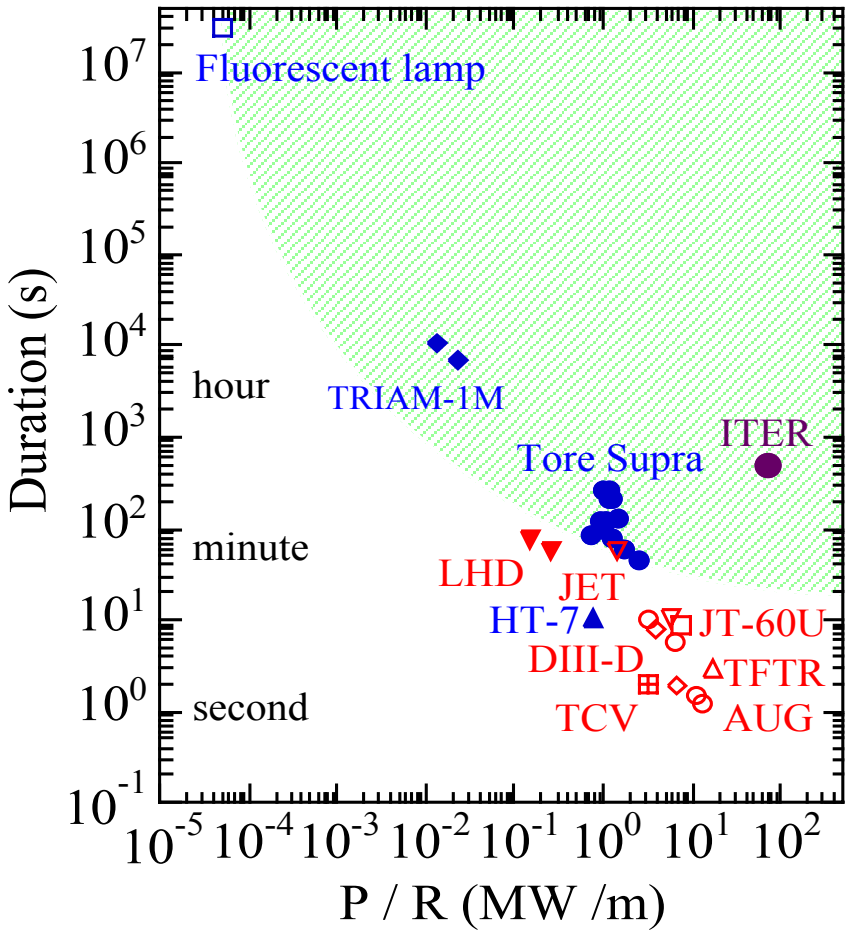
H_{98y2}~2.2, β_N~2, β_p ~2.9, f_{BS} ~80%, duration ~6τ_E



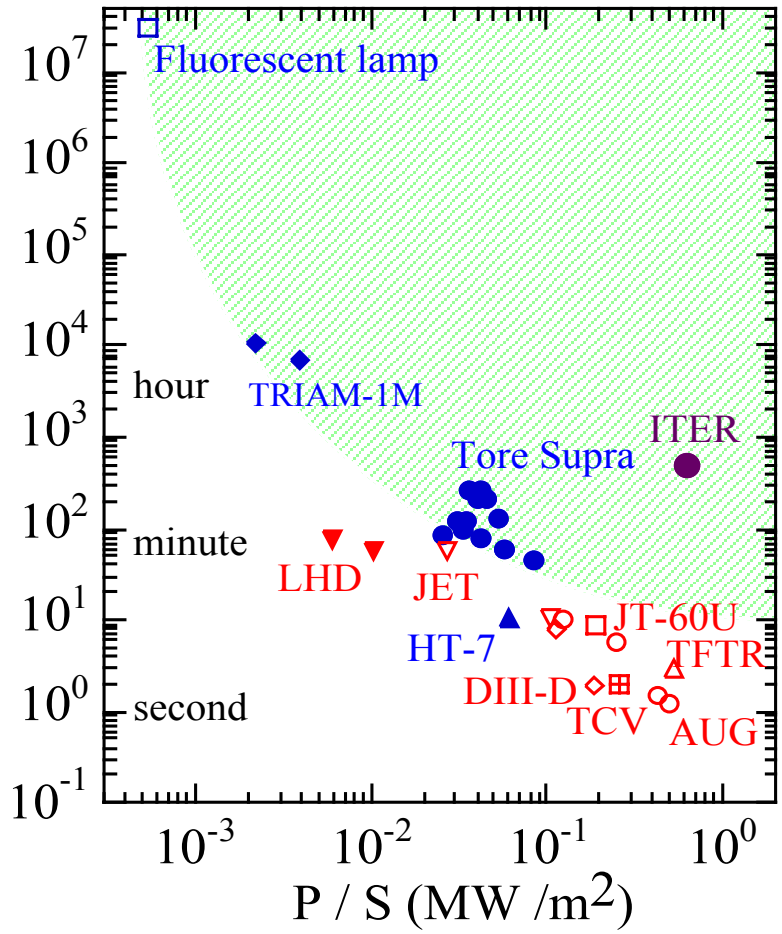


Power Handling

Convected Power



Radiated Power



inertial & actively cooled plasma facing components

Source : B. Saoutic

② MAGNETIC CONFINEMENT

Stellarators

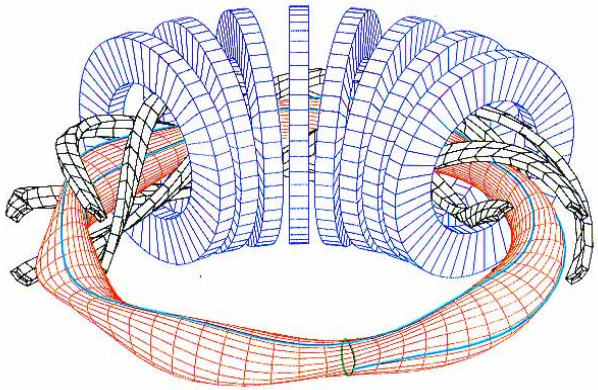
Stellarator

- Realized by currents in external coils only :
  - Steady-state operation.
  - No current driven instabilities.

- Performance of present day stellarators comparable to tokamaks, but :
  - Stellarator operation can be extended to higher densities.
  - Stellarator show quiescent nature at operational limits.

- Stellarators need optimization to be reactor relevant :
  - High neo-classical losses.
  - Low beta.

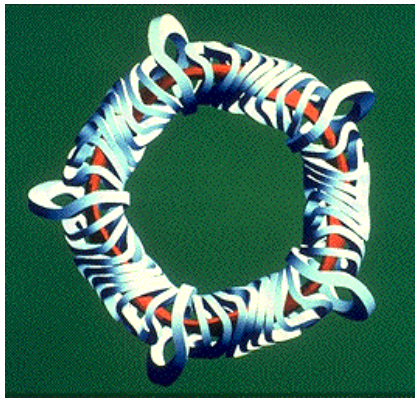
- Optimisation concept ⇒ quasi-symmetry :
  - Neo-classical losses at the level of tokamaks.
  - Low fast particle losses.
  - Improved equilibrium.



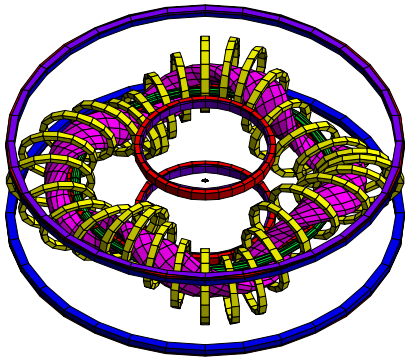
Source : F. Wagner

Helical Concepts

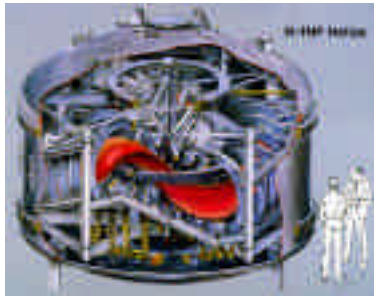
Heliotron-line of NIFS: LHD



Wendelstein-line of IPP: W7-AS



H-1 (ANU)

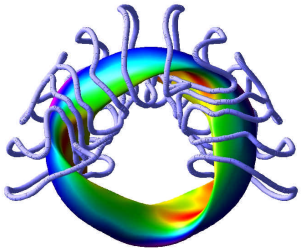


Heliacs: TJ-II (CIEMAT)

Quasi-symmetric concepts

HSX USA

NCSX USA



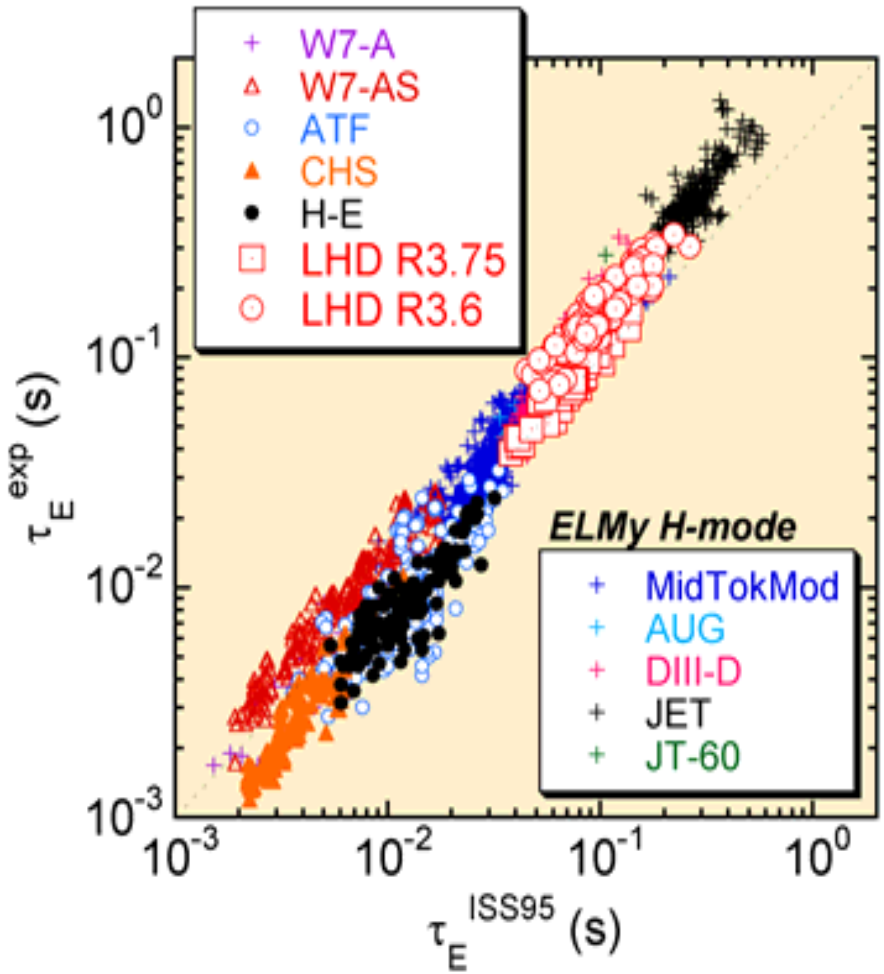
QPS USA

H-J Japan

W7-X Europe

Source : F. Wagner

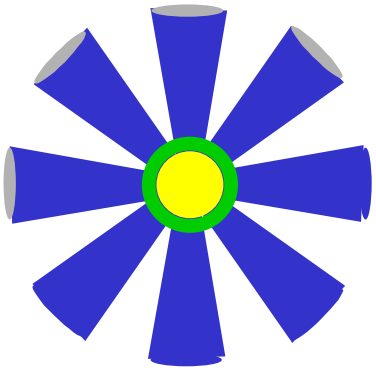
Stellarator Confinement Scaling Comparable to Tokamaks

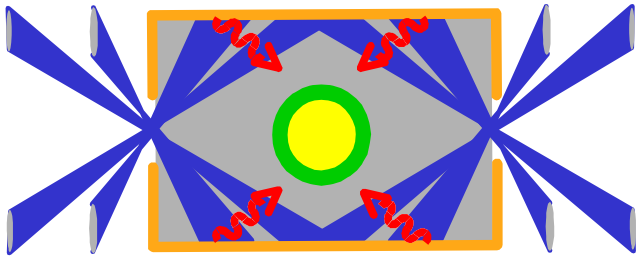


Source : F. Wagner

③ INERTIAL FUSION CONFINEMENT

Direct Drive and Indirect Drive





-	+	-	+
Weak ablation	Simple targets	Hard X rays (gold M band)	Strong ablation
Non-uniformity imprint on the shock	Low mode uniformity	Energy efficiency (backscattering and deflection)	Irradiation uniformity for high modes
Sensitivity to hydro instabilities	Fast Ignition with petawatt laser		
Suprathermal electron			

Source : J. Tassart

ICF : What has been Mastered ?

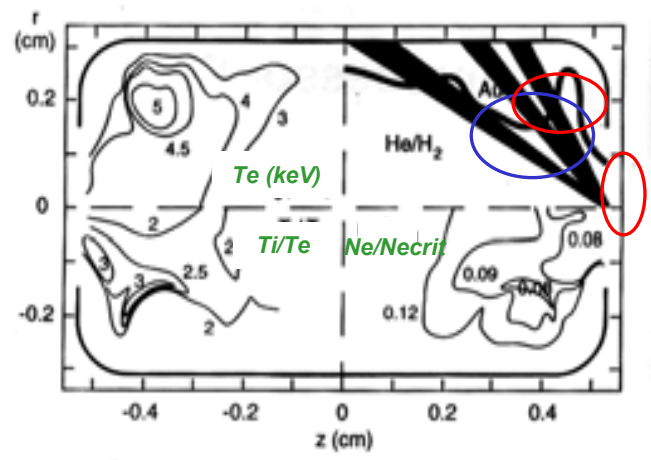
- At the beginning :
  - Laser gas breakdown : 1965.
  - Neutron emission observations : 1968-1969.
- High target compression through ablation : ρ = 100 to 600 ρ_{liquid}
- Plasma instability control using :
  - Short wavelengths : 2ω-3ω harmonics of λ = 1.06 μm.
  - Beam smoothing limiting radiation back scattering and deflection.
- Implosion symmetry and stability improvement by :
  - Laser multi-beam and beam smoothing technics.
  - Indirect drive : 300 eV hohlraum temperature controlled to 3%.
- Technology progress :
  - Megajoule NIF and LMJ conception ; operated in 2008-2010.
  - Cryogenic target realization and transport to the chamber.

Source : J. Tassart

ICF : What are the Main Ignition and Gain Issues ?

- Laser-plasma Interaction → parametric instabilities (Brillouin, Raman).

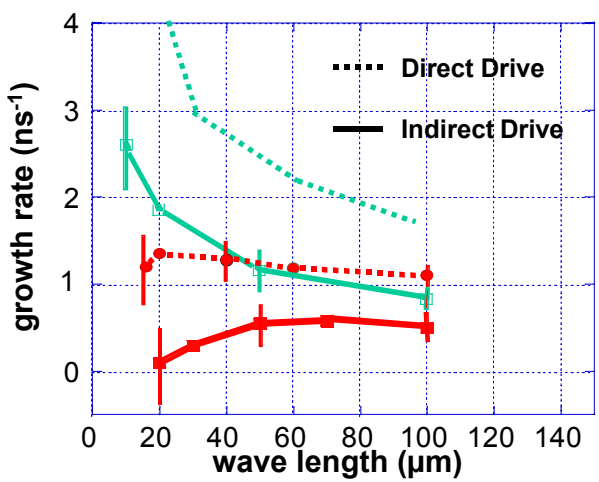
  Resonant coupling to plasma modes :
  - Light backscattering.
  - Laser beam deflection.
  - Energy transfer between crossing beams.



Raman
Brillouin

- Implosion → hydro instabilities (Richtmyer-Meshkov, Rayleigh-Taylor).
  - Capsule break-up during implosion.
  - Hot spot quenching.

  But perturbations stabilization by ablation.



Osaka,
H.Azechi, POP 4, 1997

Livermore
K.Budil, PRL 76,1996

Payload/ablator Interface

Ablation front

Evidence of stabilization by ablation

Source : J. Tassart

ICF : Other Drivers

- **High Pulse Power**

  Impressive results on Z at Sandia (US)

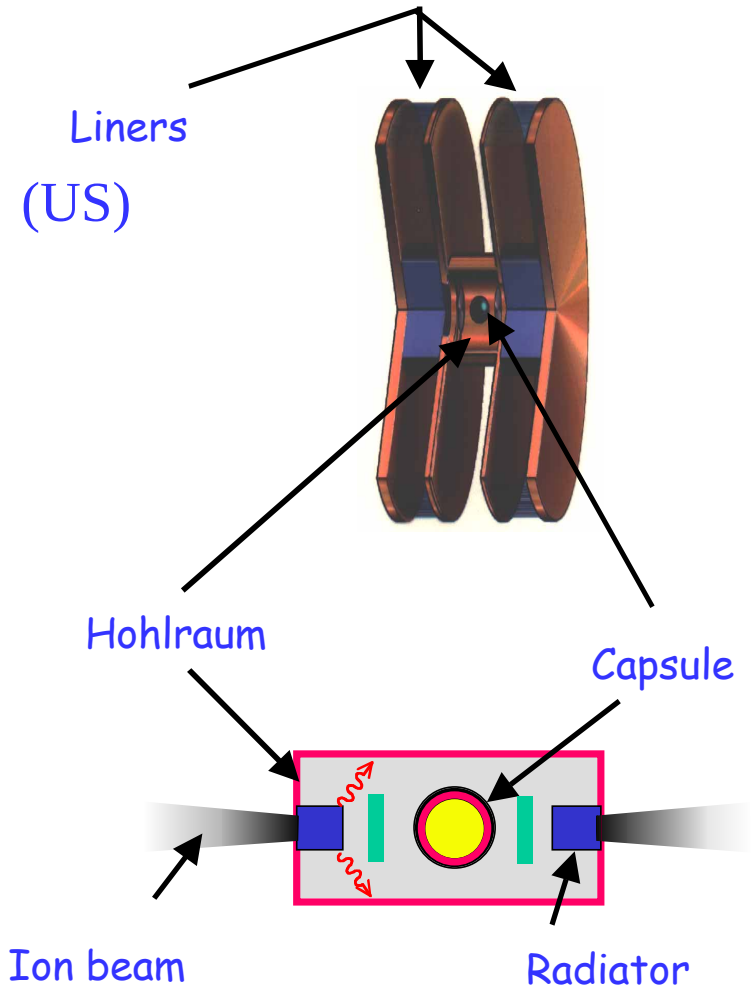
  Cavity temperature ~ 150 eV

- **Heavy Ions**

  Heavy ion accelerator facility at GSI Darmstadt (Germany)

  Integrated Beam Experiment Project in the US

  High repetition rate potential capability necessary for IFE power plant.



Source : J. Tassart

ICF : Megajoule Lasers

NIF building
March 2000

LIL building
2000

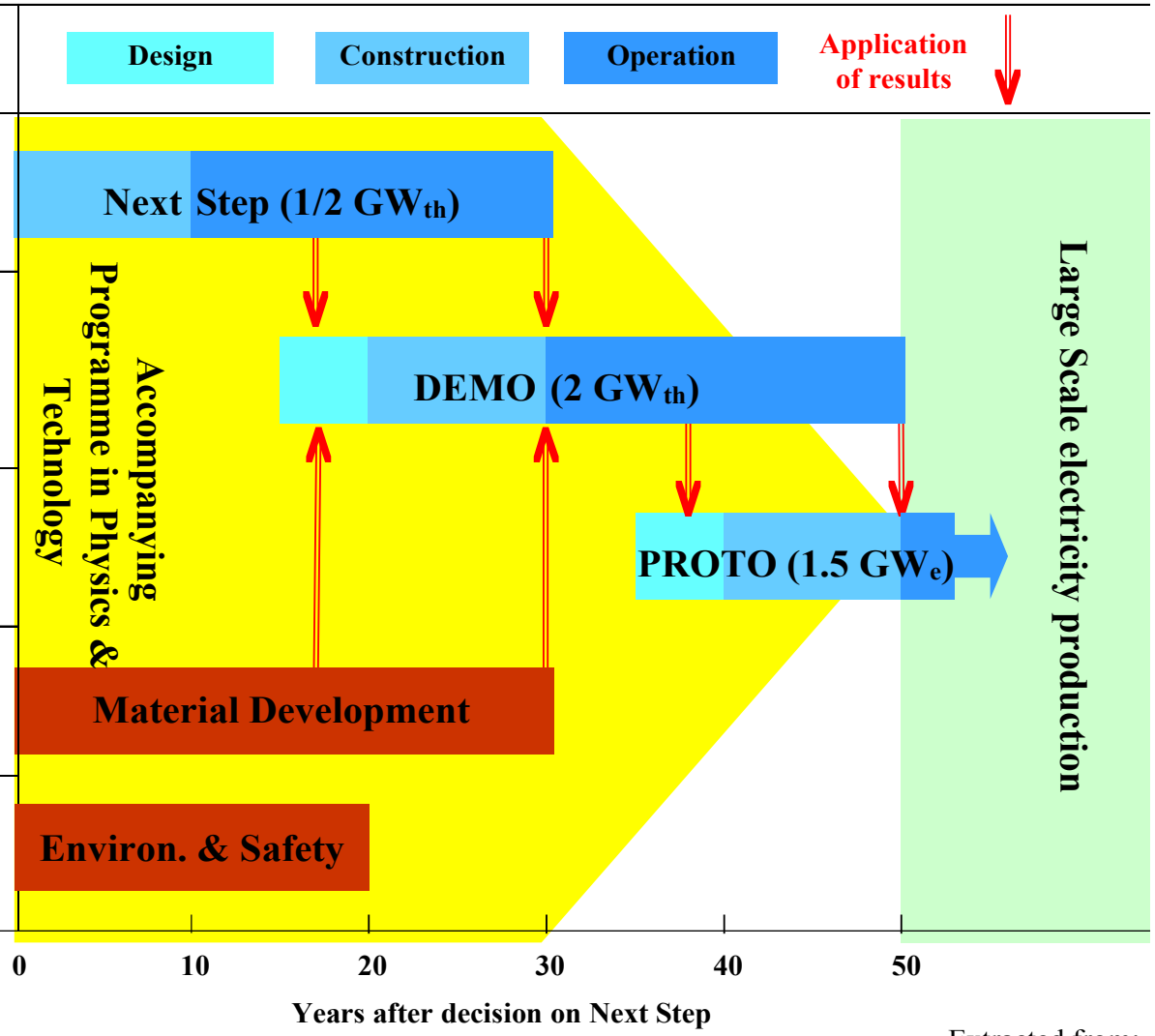
Source : J. Tassart

④ THE ROAD TOWARDS THE REACTOR :

ITER

Tentative Roadmap of Achievements starting from the decision to construct the Next Step

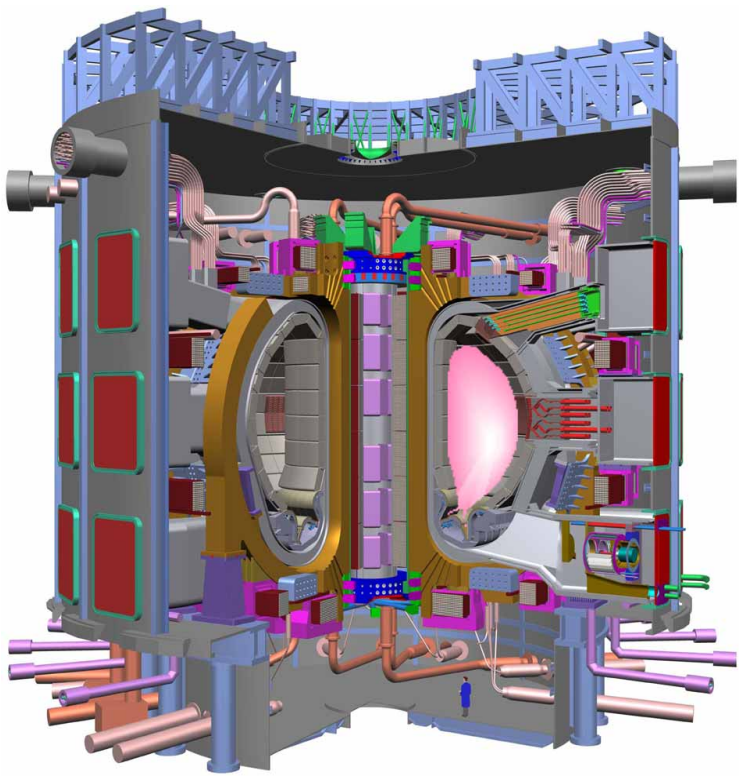
Main Achievements Required
〈 Production and control of long pulse-burning plasma 〈 Heat and particles exhaust (plasma facing components) 〈 Test of breeding blanket modules for DEMO
〈 Net electricity production (full hot breeding blanket) 〈 High reliability of operations 〈 Qualification of lower activation materials for PROTO
〈 Improved economy in electricity production 〈 Improved low activation materials
〈 Demonstration of a reference low activation steel for DEMO 〈 Search for higher performance materials for PROTO
〈 Demonstration of waste management and recycling 〈 Demonstration of safety management 〈 Demonstration of low environmental impact potential



Extracted from:
"Five Year Assessment Report related to the specific programme: Nuclear energy covering the period 1995-1999" June 2000

ITER

Four Parties : Canada, European Union, Japan, Russian Federation



$R = 6.2$ m

$a = 2.0$ m

$B_T = 5.3$ T

$I_p = 15$ MA

Duration (with CD) $\geq$ 400 s

$E_{fusion} = 500$ MW

$Q \geq 10$

ITER Objectives

(from IAEA Final Design Report, FDR)

- Overall :

  To demonstrate the scientific and technological feasibility of fusion energy.

- Plasma :

  - Q ≥ 10, 300 – 500 s (inductive ELMy H-mode).

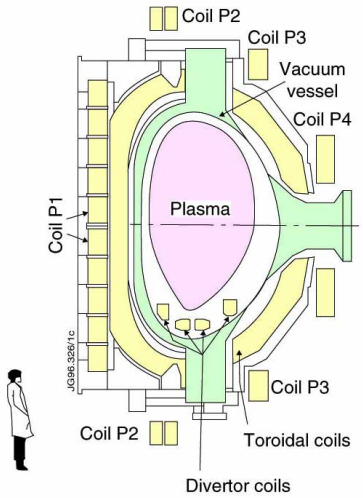
  - Q ≥ 5, steady-state (non-inductive current drive).

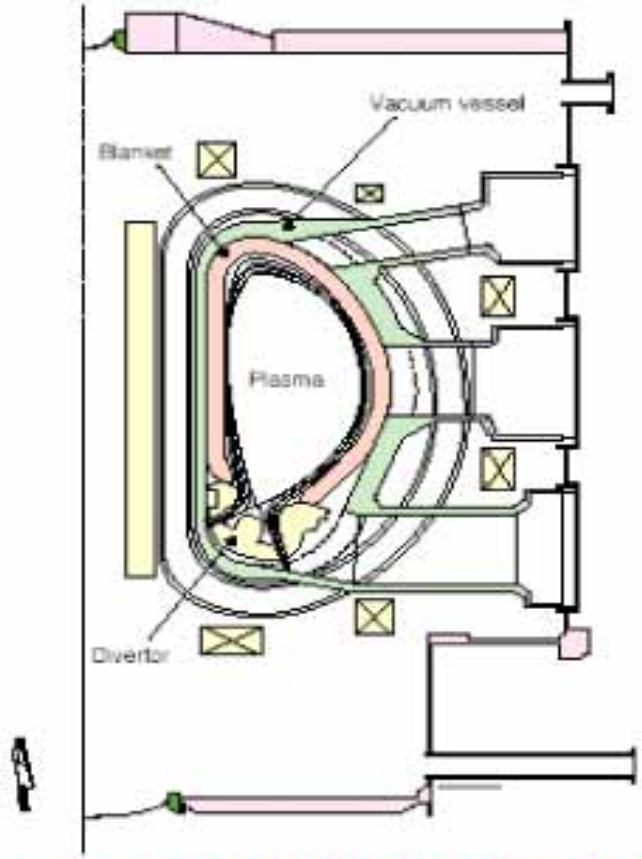
- Technology :

  - To test the components of a fusion reactor :
    neutron flux ≥ 0.5 MWm^{-2}, neutron fluence ≥ 0.3 $MWam^{-2}$

  - To test the tritium breeding blanket concept.

Poloidal Cross-sections of ITER and JET





JET

R = 3m; I = 6MA

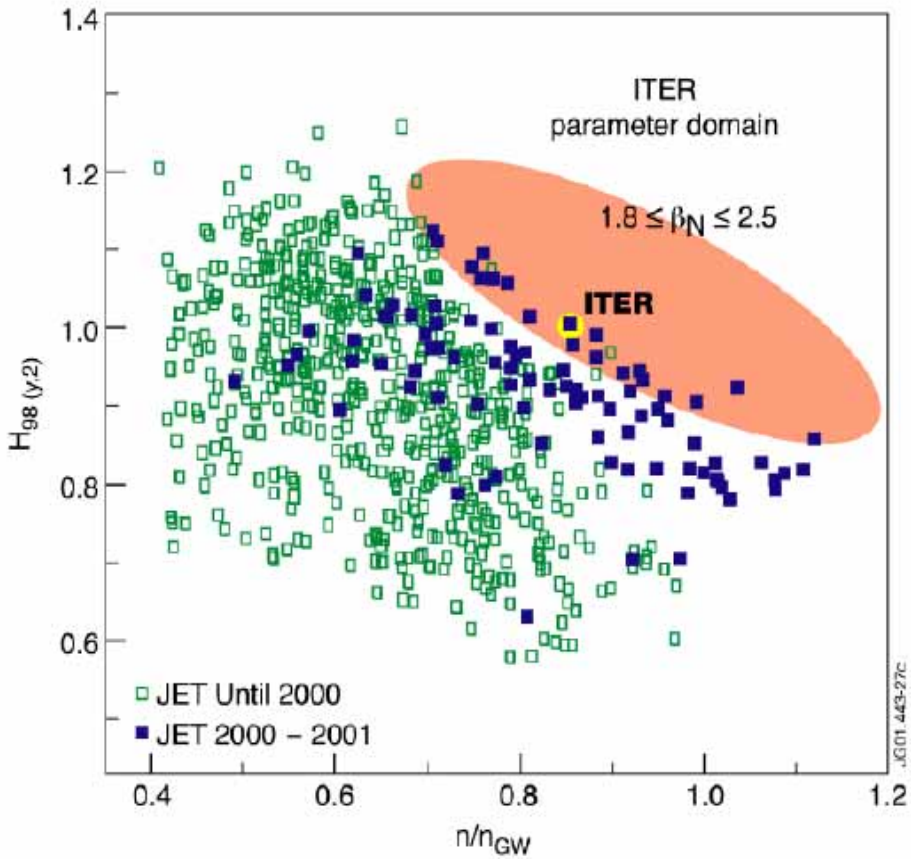
Plasma Volume = 80 - 100 m^3

ITER-FEAT BURNING PLASMA

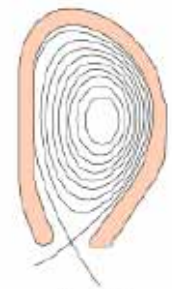
R = 6.2m; I = 13MA

Plasma Volume ~ 840 m^3

Q =10 : ITER-Simulation Discharges on JET



JET-operating space

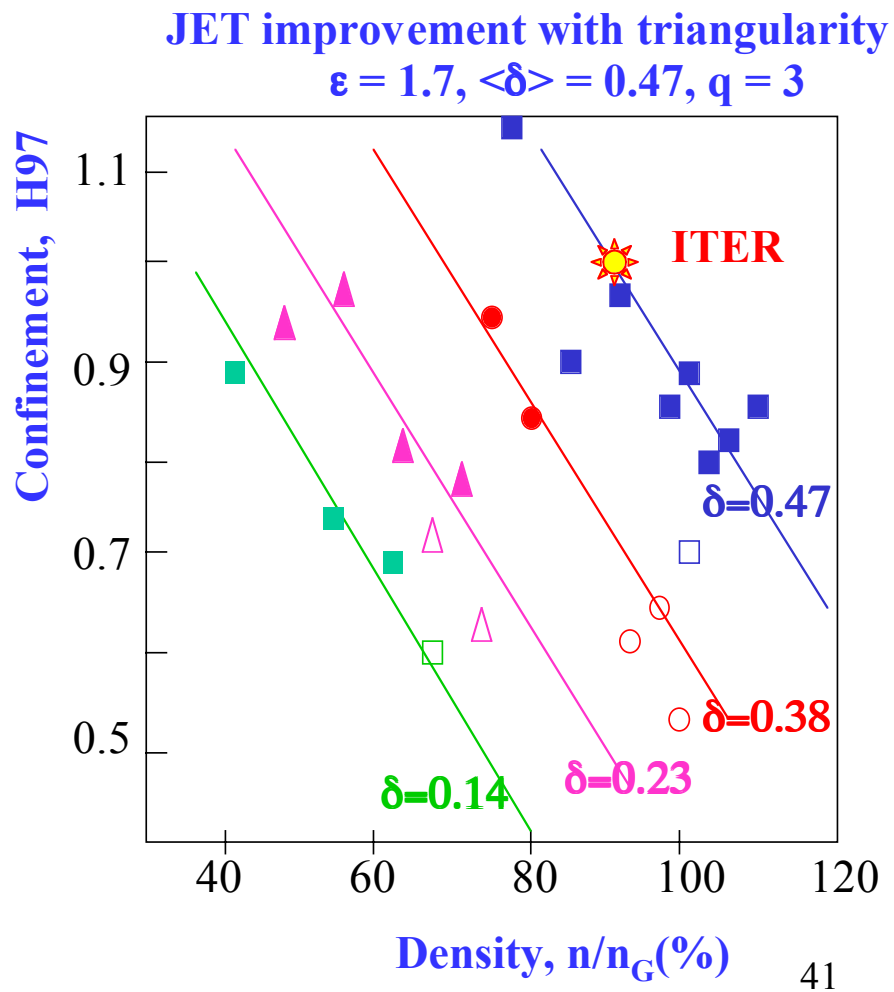
SHAPING		
		
	JET "ITER shape" Pulse No: 53299, 2.5MA/2.7T	**ITER**
$H_{98\,(y,2)}$	0.91	1.0
$\beta_{N,th}$	1.90	1.81
n_e / n_{GW}	1.1	0.85
Z_{eff}	1.5	1.7
P_{rad} / P_{tot}	0.40	0.58
κ, δ	1.74, 0.48	1.84, 0.5
q_{95}	3.2	3.0
τ_{pulse} / τ_E	15	110

Source : K. Lackner

Reference Operational Scenario for ITER :
ELMy H-mode with divertor

Main issues :

- α-physics.
- Divertor lifetime with large ELMs.
- Tritium retention in the divertor.
- Neo-classical tearing modes controlled by ECRH.

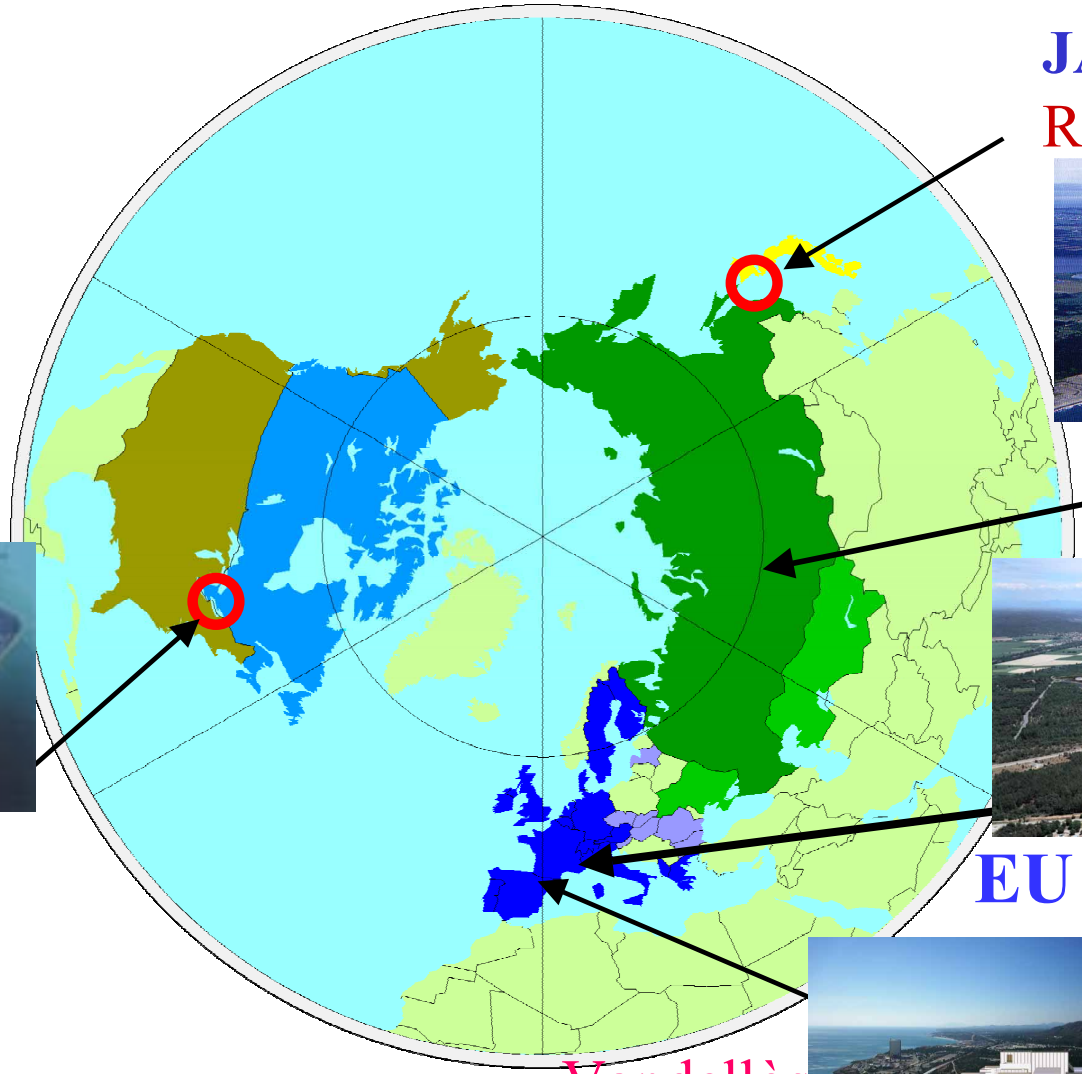


Source : Saibene et al

ITER Negotiations

- ITER is a 40 years international challenge ;
  It requires a € 4.6 billion investment.
- Parties are Canada, European Union, Japan and Russian Federation ; US and China might join.
- Objective : settle a « Joint Implementing Agreement » (JIA) dealing with ITER status, site, participation, licensing...
- Sites : Clarington (CA), Cadarache (EU), Rokkasho (JA), Vandellos (EU) are offered ; a “preferred site” will be proposed early in 2003.
- Launched in November 2001, the negotiations could be achieved mid-2003 ; the JIA agreement will be then submitted to the Party Governments for signature.

ITER Partners and Potential Sites



JAPAN
Rokkasho

RUSSIA

EU Cadarache

CANADA
Clarington
(Ontario)

Vandellòs

Strategy Towards the Reactor

- ITER, a Q = 10 burning plasma, is a first priority.
- To reach the ITER goals and to select on the long term the fusion reactor configuration, it is mandatory to develop an "accompanying programme".

  Superconducting facilities will contribute to the steady-state work : TS (EU), LHD (JA), HTU (China), JT60 SU (JA), KSTAR (Korea), SST (India), W7-X (EU).
- Reactor technology issues have to be solved at a pace depending on the investments allowed ; a "Fast Track" could be contemplated with a reactor goal for the 2050 horizon.

Fast Track

The European "Fast Track" Group concluded that the ITER-PROTO time period could be shortened by about 10 years, by :

- Starting ITER without delay.
- Performing already on ITER testing of tritium breeding and energy extraction systems, with increased emphasis on high performance, steady-state operation.
- Combining in a single step some aims of the DEMO and PROTO generations : in particular achieving reliability of operations closer to commercial requirements.
- Proceeding with the development of adequate materials in parallel to the ITER and DEMO/PROTO generations.

Conclusions

① Research has established a well founded physics and technology fusion basis.

High fusion performances have been realized, reaching 16 MW of peak power and 20 MJ of energy.

② Today, the demonstration of a sustained burning plasma is the next goal which opens the route towards the reactor.

③ To reach this goal, we have essentially to choose a site for ITER, conclude its negotiations and launch its construction in the near future.

④ Strengthening the international broad-based collaboration is the key to harness the benefits of fusion for mankind.