Alfred Nobel Symposium
Energy in Cosmos, Molecules and Life

Whatever became of Nuclear Fusion?

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18-22 June 2005

Stockholm

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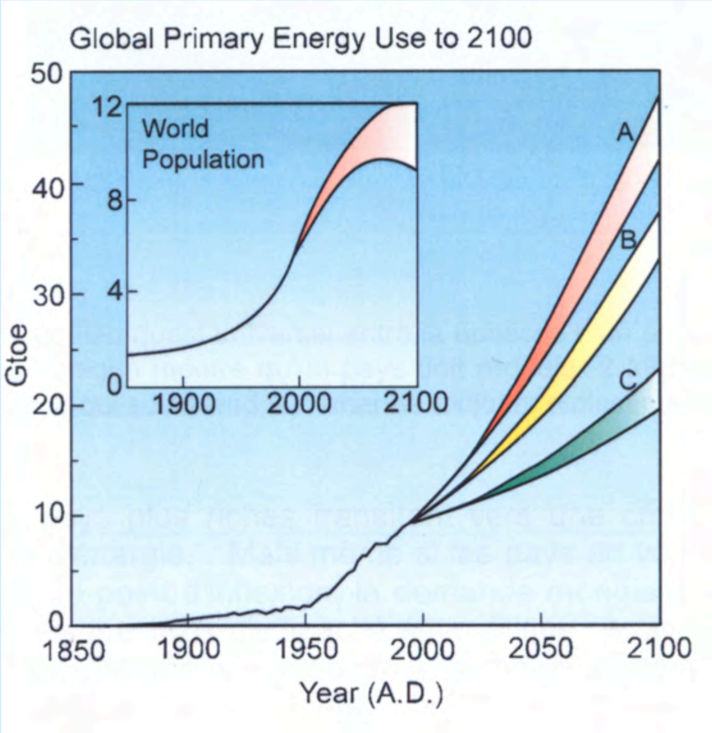
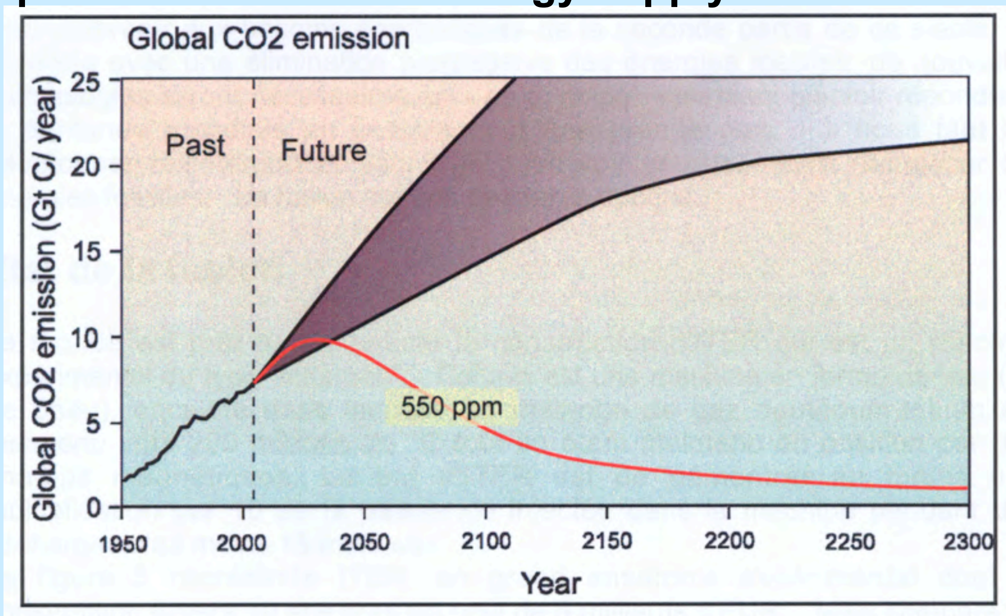
Whatever became of Nuclear Fusion?


There is a popular view that fusion energy has
been just over the horizon for decades,
and that it has failed to deliver.
This is false!
Fusion has always been a long-term project.
We have learned a great deal, scientific progress
has been impressive, and the potential for energy
generation is real.

The need for new energy sources

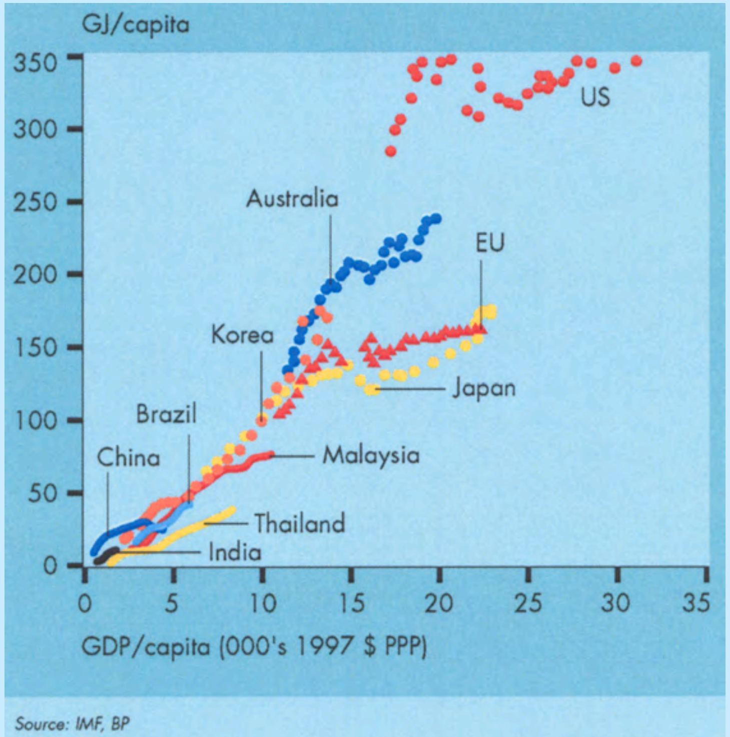
The projected increase in the world's population is accompanied by a dramatic increase in energy consumption.
Scenarios A, B and C correspond to high growth, a middle course, and an ecologically-driven global energy policy.
All require new sources of energy supply.



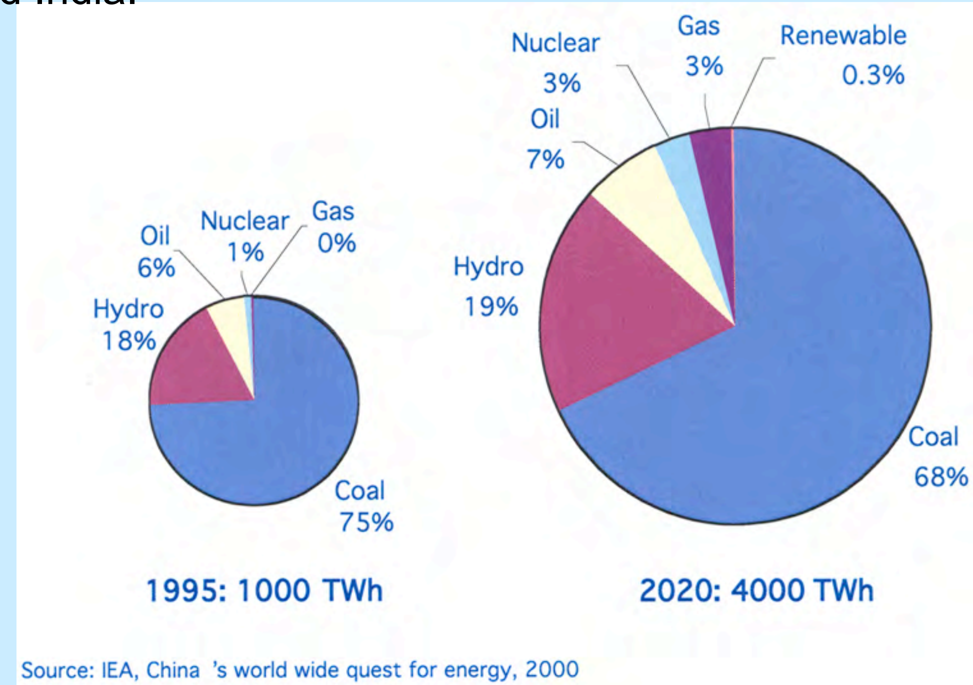


Projections based on current energy supply, enclosed within the black lines, do not allow atmospheric CO_2 concentrations to be controlled.
To stabilise at 550ppm, emissions must soon start to fall dramatically (red line).
This can only be achieved with an energy supply that emits zero greenhouse gas.

The need for new energy sources



There is a clear correlation between energy consumption and national wealth.
This will lead to an explosion in demand in developing economies - a phenomenon that is already being seen in China and India.



Today, China generates three quarters of its energy from coal, with hydro accounting for 18%.

By 2020, this is projected to evolve, but only slightly, though energy production will have quadrupled. Coal will still be dominant, and despite high-profile projects such as the three gorges dam, hydro will advance by just 1%. **New energy sources are clearly needed.**

If the energy supply industry is to satisfy demand, while restricting atmospheric $C0^2$ to 550ppm, besides coal-burning plant with total sequestration of the CO^2 produced, fusion reactors (in concurrence or competition with possible new scheme of nuclear fission) must progressively replace conventional power stations from around 2050.

For this to happen, the international ITER fusion project is a necessary next step.


Fusion is the power source of the stars.
In the Sun, the primary reaction combines hydrogen into helium.
For controlled fusion on Earth, the heavier isotopes of hydrogen - deuterium and tritium - are more suitable fuels.

Fusion has many appealing features

It is environmentally friendly - no greenhouse gases

No long-lived radioactive by-products

No chance of runaway reactions

A very small fuel inventory

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Whatever became of Nuclear Fusion?

What is Controlled Nuclear Fusion?

- **Nuclear Fusion, besides gravity, is the essential energy source for the universe**
- It is the power source of the stars, which burn lighter elements into heavier ones with the release of energy
  - in the sun, 600 Mt/s of hydrogen combines into helium with a small mass decrease
  - $4\ {}^1H \rightarrow {}^4He + 2e^+ + 2\ \nu_e + 26.7$ MeV (1 MeV= 1.6 10^{-13} J)
- **For controlled fusion on earth, that process is much too slow; heavier isotopes of hydrogen should be used and the easier process is :**
  - $\mathbf{{}^2D + {}^3T \rightarrow {}^4He\ (3{,}5\ MeV) + {}^1n\ (14{,}1\ MeV)}$
  - $6\ L_i + {}^1n \rightarrow {}^3T + {}^4He$ (+ 4,8 MeV)
  - $7\ L_i + {}^1n \rightarrow {}^3T + {}^4He + {}^1n$ ($-$2,5 MeV)
- research efforts focus on achieving three conditions together:

density

bring enough particles into proximity

temperature

give them enough energy to fuse

confinement time

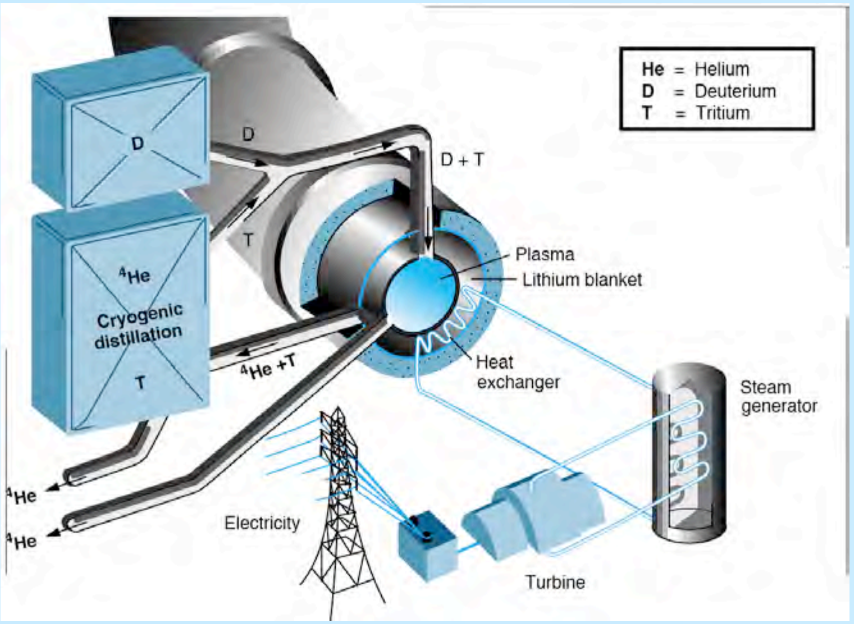
keep them together for long enough

Two generic implementation concepts are pursued experimentally to achieve those conditions using two schemes of confinement: **magnetic and inertial**, the first more advanced than the second.

Concept to develop Nuclear Fusion

1. **Magnetic confinement for steady state:**

- the fuel (D+T) takes the form of a hot plasma inside an appropriate magnetic field configuration in order to limit heat and particle losses
- the process is a nuclear combustion (similar conceptually to a chemical combustion)
- the density is small (10^{20} p/m^3) and the pressure ~ 1 bar
    - o ^4He produced (20% of the fusion power) remains in the plasma and stabilises the temperature T against power losses
    - o ^1n produced (80% of the fusion power) leaves the volume and provides the usable energy, it is slowed down in a cooled "blanket", before being absorbed by the Lithium at low energy and reproducing the tritium. **The power balance writes:**



$$\underbrace{\frac{1}{4} n^2 R(T) \frac{E_F}{5}}_{\text{fusion power}} \underbrace{\left(1 + \frac{5}{Q}\right)}_{\text{auxiliary power}} \geq \underbrace{\frac{3nT}{\tau_E}}_{\text{power losses}}$$

$$n\tau_E T \geq \frac{60T^2}{E_F R(T)(1+\frac{5}{Q})}$$

$n = n_e \quad n_D = n_T = \frac{ne}{2}$ Plasma density

T temperature

R(T) reaction rate

$\frac{E_F}{5} = 3.5\mathrm{MeV}$

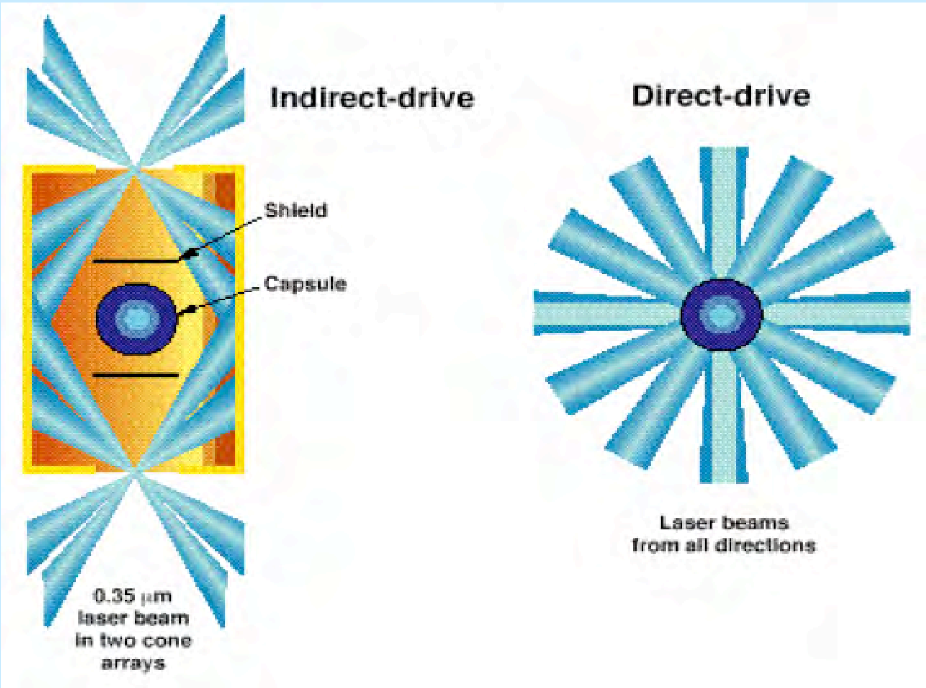
$0 < Q = \frac{P_F}{P_{aux}} < \infty$

$$\boxed{n\tau_E T \geq \text{ minimum for } T \approx 1.5 \times 10^8 \mathrm{K}}$$

Concept to develop Nuclear Fusion

2. Inertial confinement during very short pulses:

- a small pellet of fuel (D+T) is compressed and heated by intense laser or ion beams (direct or indirect drive)
- the density is very high (~ 1000 n_{ice}) and the pressure (~M bars)
- from the hot pellet centre, a burning wave propagates radially supported by the He power; this time the energy balance should be considered with a gain G



$$G = \frac{E_{Fusion}}{E_{input}}$$

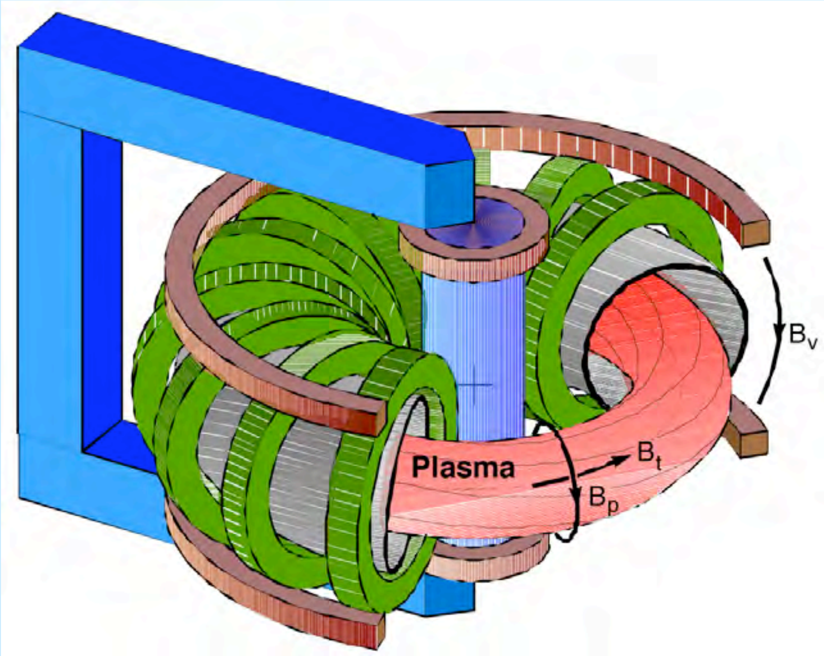
large enough $\geq$ 50 - 100

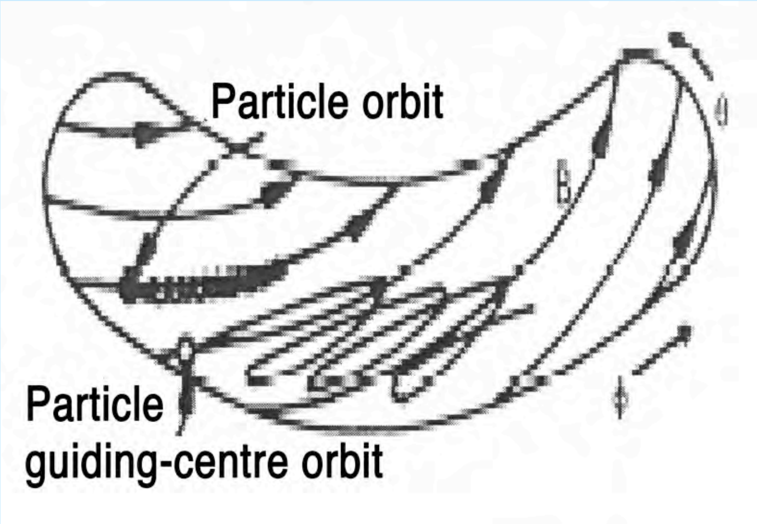
$$n \tau_E T \geq \frac{T}{R(T)}$$

the minimum is obtained for $T \simeq 3 \times 10^8$ K

Physics mechanisms present in toroidal magnetic confinement (Tokamak) - 1

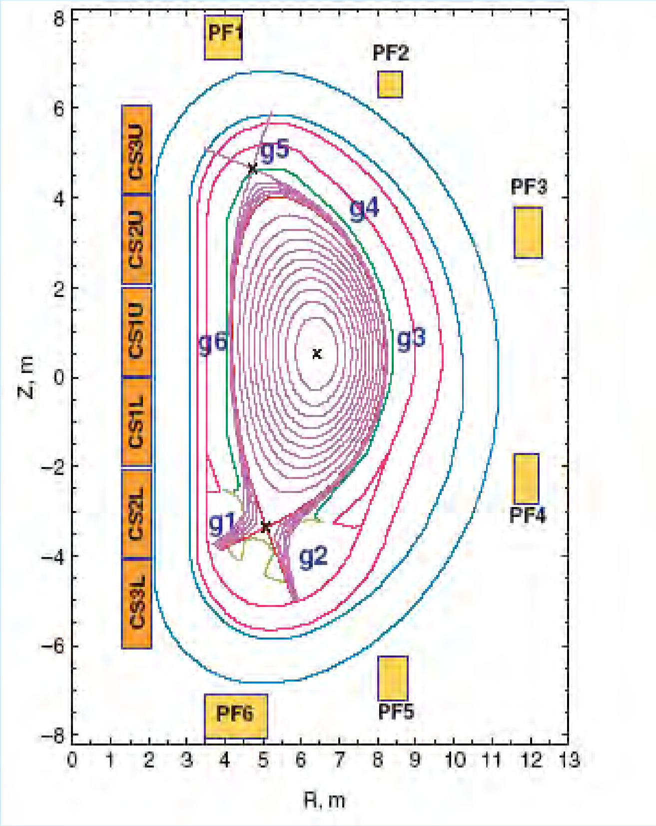
- **single particles are confined** in the torus, as long as there is a **rotational transformation in the topology of the magnetic lines:** a poloidal magnetic field (due to toroidal plasma current) added to a larger toroidal component
- **The particle motion is periodic** (3 frequencies associated)





Physics mechanisms present in toroidal magnetic confinement (Tokamak) - 2

- **magnetic surfaces** are created, nested around a magnetic axis, **which are isobar and isotherm of the plasma**
- across these magnetic surfaces, there are **current density (j) and pressure (p) profiles providing an equilibrium**



Limits of plasma confinement = stability of equilibrium

1. **the linear stability of this macroscopic equilibrium controls the operational domain of the tokamak**; the plasma behaves as a fluid, this is magneto hydrodynamics - two sources of instability: ∇ j and ∇ p.
   - ∇j drives "tearing modes" which change the topology (creation of islands) and can be controlled.
   - ∇p drives "interchange modes", which limit the value of $\beta = \frac{p}{B^2}$ (to a few %)
2. **the non-linear development** of these instabilities depends on the **magnetic shear**, it drives in general **relaxation oscillations and magnetic reconnexion**, (not completely understood)

similar phenomena are at work during solar eruptions,
in the magnetosphere, in magnetised accretion disks.

3. **Transport phenomena** (particles, heat, momentum) across the magnetic surfaces control the plasma losses
   - this is a **turbulent transport due to micro instabilities**, with "vortex cells" of the size of a few ion gyration radii. They are driven by waves, "drift waves“ which can be in resonance with the particle motion frequencies and some part of their velocity distribution.
   - again the source of these instabilities is the **pressure gradient of some category of particles** (electrons, ions, high energy ions as He from fusion reaction)

Limits of plasma confinement = turbulent transport

The international collaboration put all data together from all existing Tokamaks **to end up with scaling laws**, to deduce the plasma energy confinement from physical parameters. (B, I, n, P, a, R, etc.)

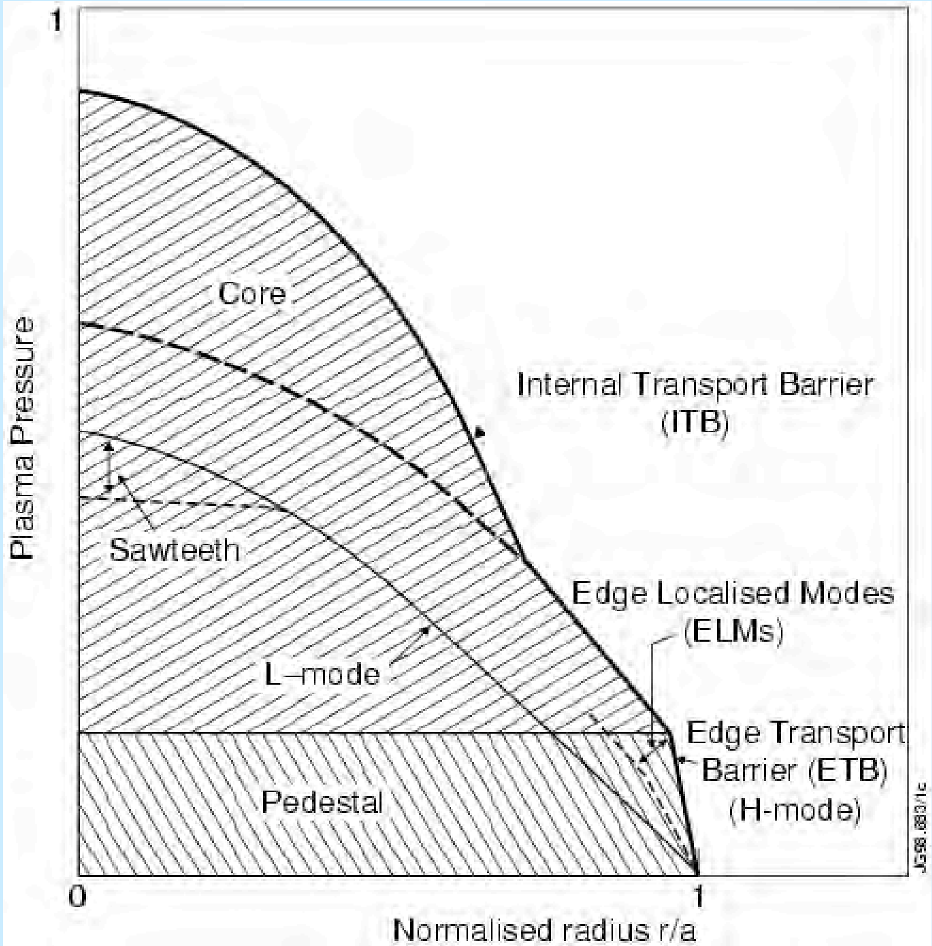
This empirical method received support principally by successfully confronting it with **relations built from non-dimensional parameters** (a kind of “wind tunnel” analysis).

$$B\tau_E \propto \rho_*^{-3}\beta^{0}\nu_*^{-0.35} \quad \text{with} \quad \rho_* = \frac{\rho_{\text{ion}}}{a},\ \nu_* = \frac{\tau_{\text{collision}}}{\tau_{\text{period}}},\ \beta$$

The consequences of these instabilities are a limiting factor to the confinement of energy, a vital issue for the possibility of using nuclear fusion as an energy source.

Limits of plasma confinement = transport barriers

Improvements to the value of τ_E come from the existence of generic transport barriers : the transport becomes self limited by the non linear development of the instabilities when the ∇j or ∇p is forced to larger values, and produces **a shear in magnetic field** (close to the separatrix) **or in velocity.**



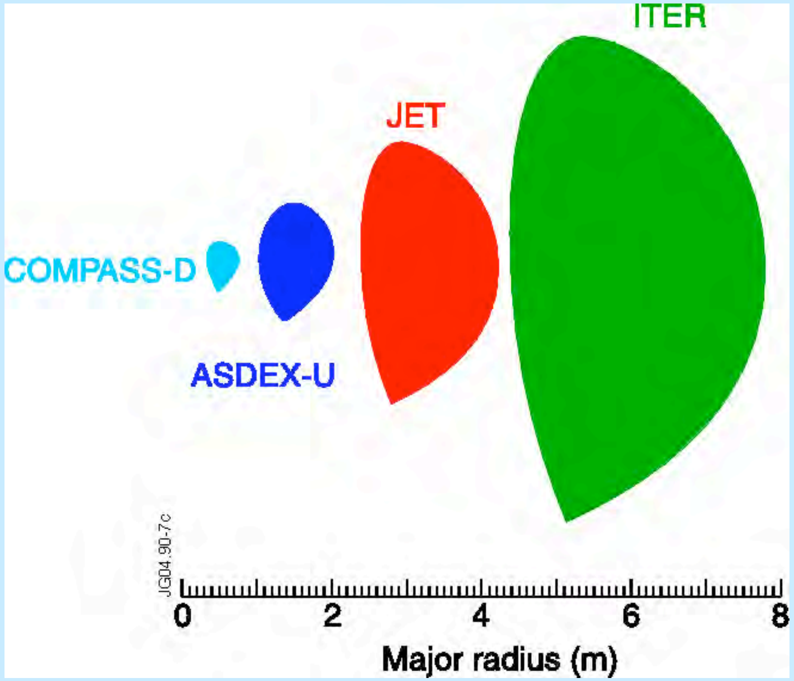
Relations with other physics domains

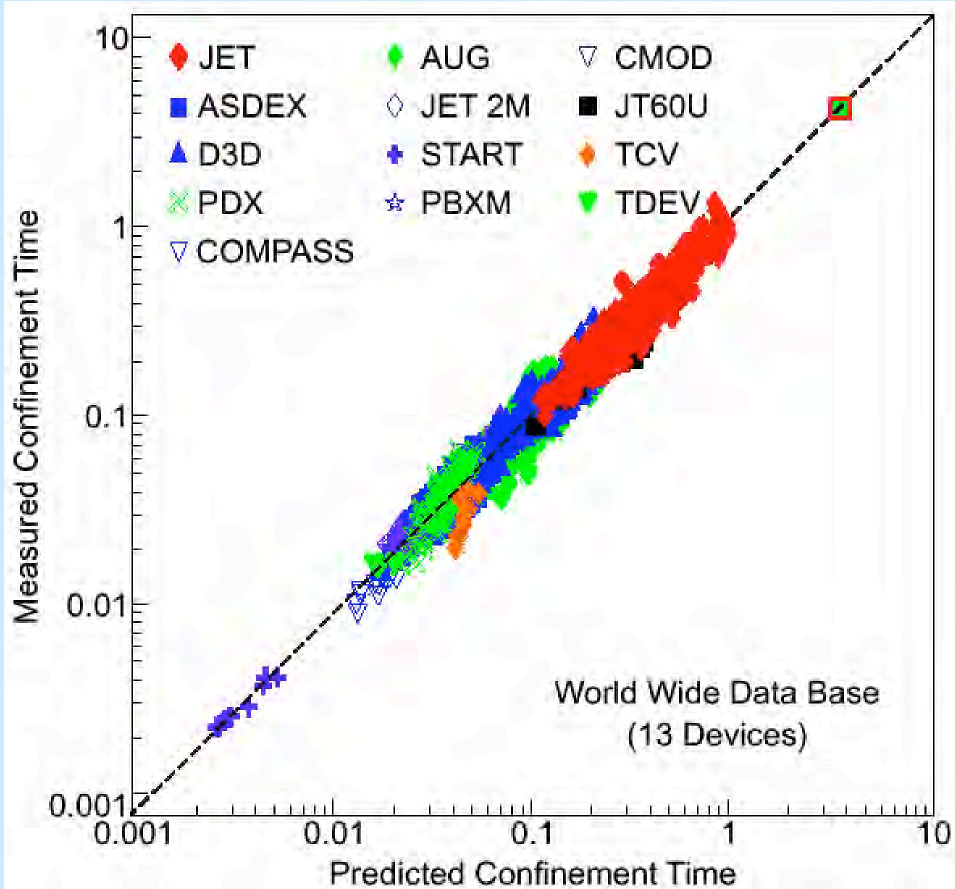
- Strong analogies with fluid turbulence in particular with the turbulence of a fluid in rotation (atmospheric turbulence)

- In astrophysics, the turbulent viscosity assumed in the models of stellar formation

Experimental results

The results from all experiments running at present show, in particular, the global value of τ_E, across more than two orders of magnitude, as function of physical parameters linked by an **experimental "scaling law".**





Conditions for the best experimental results

- The largest machines JET (Joint European Torus) and JT60 (Japanese Torus) have achieved **the best plasma performances**, where **$Q = P_F/P_{aux}$ is close to breakeven**. JET has produced 16 MW of D-T fusion power transiently.

- The successful operation of the **divertor concept** limited **the influx of impurities** in the plasma and provided the **plasma exhaust** (particles and thermal energy).

- The development of **powerful plasma heating methods**, by multimegawatt injection of electromagnetic waves or high energy neutrals. **Numerous diagnostic methods** and measuring instrumentation provided the necessary tools.

- At present, operations of the largest machines, like JET and JT60, are mostly steered to **simulate the best conditions for ITER operation in quasi-stationary plasma conditions, with a low level of fluctuations.**

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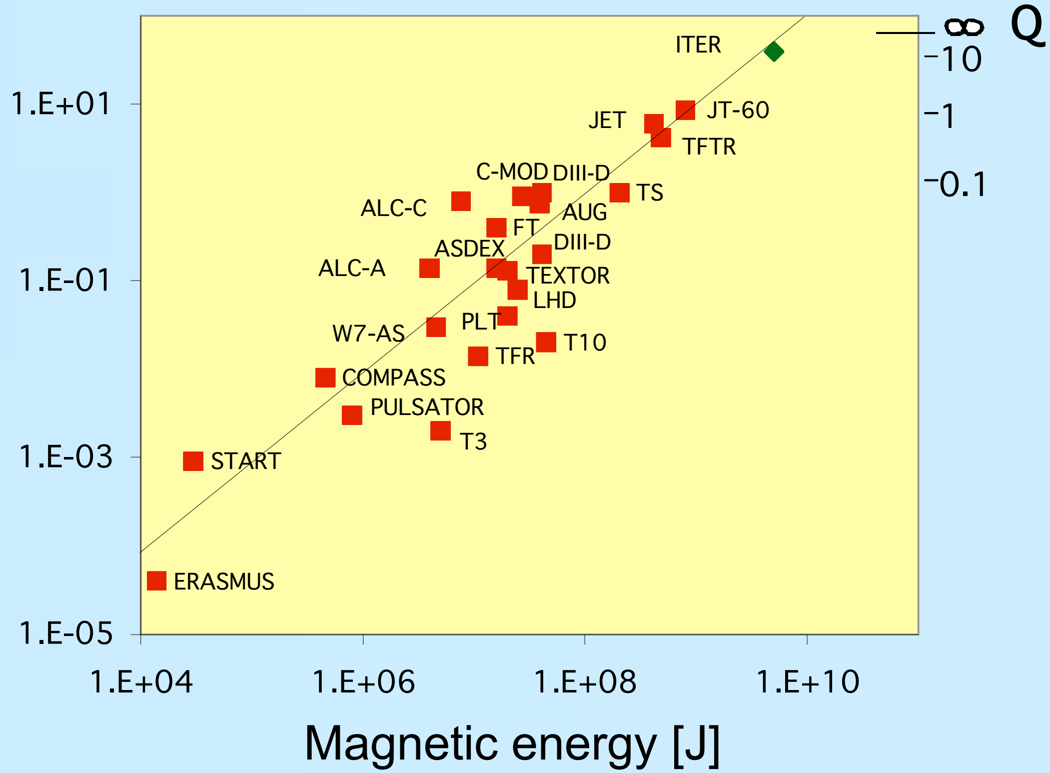
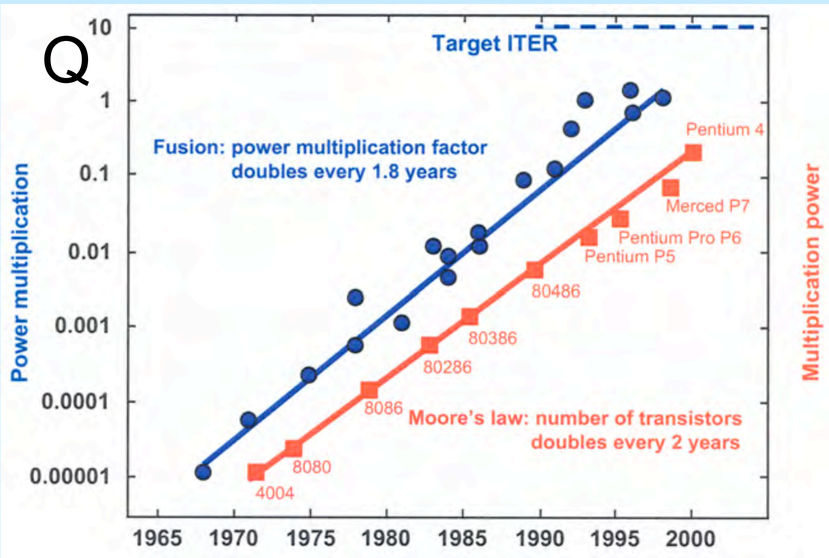
Whatever became of Nuclear Fusion?

Why ITER? Why now?
Past achieved plasma performances

Triple product
n τ_e T
[10^{20} m^{-3} s keV]

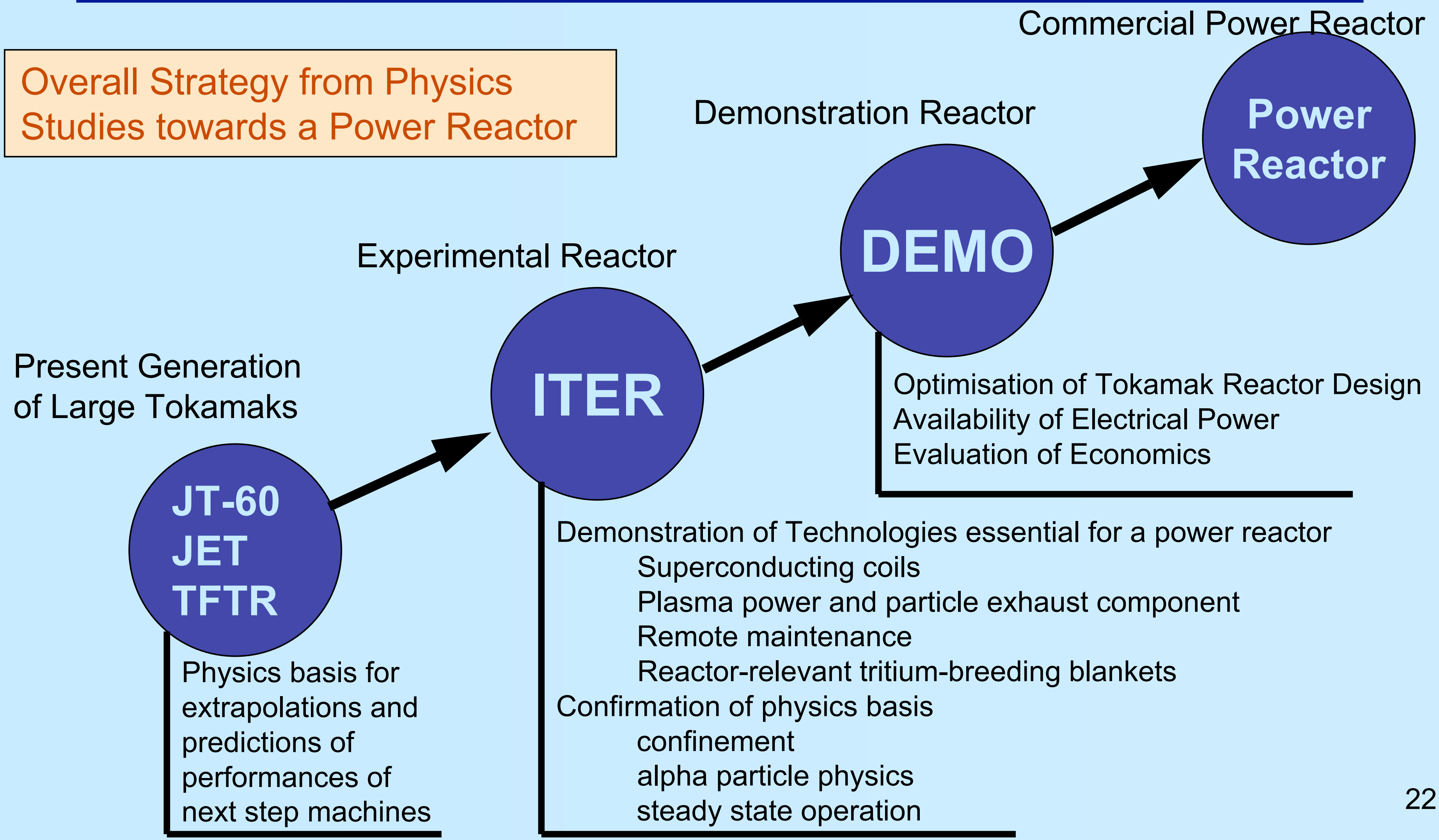




nτT and Q values reached by Tokamak devices versus the magnetic energy stored in their plasma volume.

Why ITER? Why now?

Overall Strategy from Physics Studies towards a Power Reactor



Why ITER?

At the world level, **only one strategy appeared sensible** (more deeply with time) and confirmed:

- the building of a large enough device according to the present understanding to obtain a burning plasma.
- the validation and optimization of the physics parameters for a possible future electricity generating Demonstration Reactor.
- the development of technologies necessary for this future reactor.

This device, a physics experiment and an experimental reactor, should demonstrate the scientific feasibility of fusion as an energy source.

ITER

The present experiments are able to simulate (not necessarily simultaneously) most plasma parameters □, □, n, T, j, B which control the plasma performance, all of them being relevant to a power reactor.

Nevertheless, one effect cannot be experimentally checked, due to the non-linear coupling, inside the plasma volume, between the internal heat source (from He particle, 20% of the fusion power) and the global behavior of the plasma according to its diffusion controlled profiles.

The ITER project

- initiated in summit discussions: Gorbachev, Reagan, Mitterrand
- **Conceptual Design Activities** (1988-90) **Engineering Design Activities** (EDA) under Inter-governmental Agreement 1992-2001 - IAEA auspices
  - four equal founding Parties (EU,JA,RF,USA) for initial term of Agreement to 1998; then three Parties (EU, JA, RF) for extension period to July 2001
- design work shared between a distributed Joint Central Team and four “Home” Teams; supporting R&D by Home Teams
- full output available to each Party to use alone or in collaboration
- July 2001 - a **“detailed, complete and fully integrated design of ITER and all technical data necessary for future decisions on the construction” are documented** (IAEA series)
  Negotiations are started between parties, joined by USA again, China, Korea
- **These results were achieved at the expenditure of $ 660 M (1989 values, USA $ 120 M) on R&D and 1950 (USA; 350) professional person years of effort.**

ITER Objectives

Programmatic

- Scientific and technological feasibility of fusion energy for peaceful purposes.

Technical

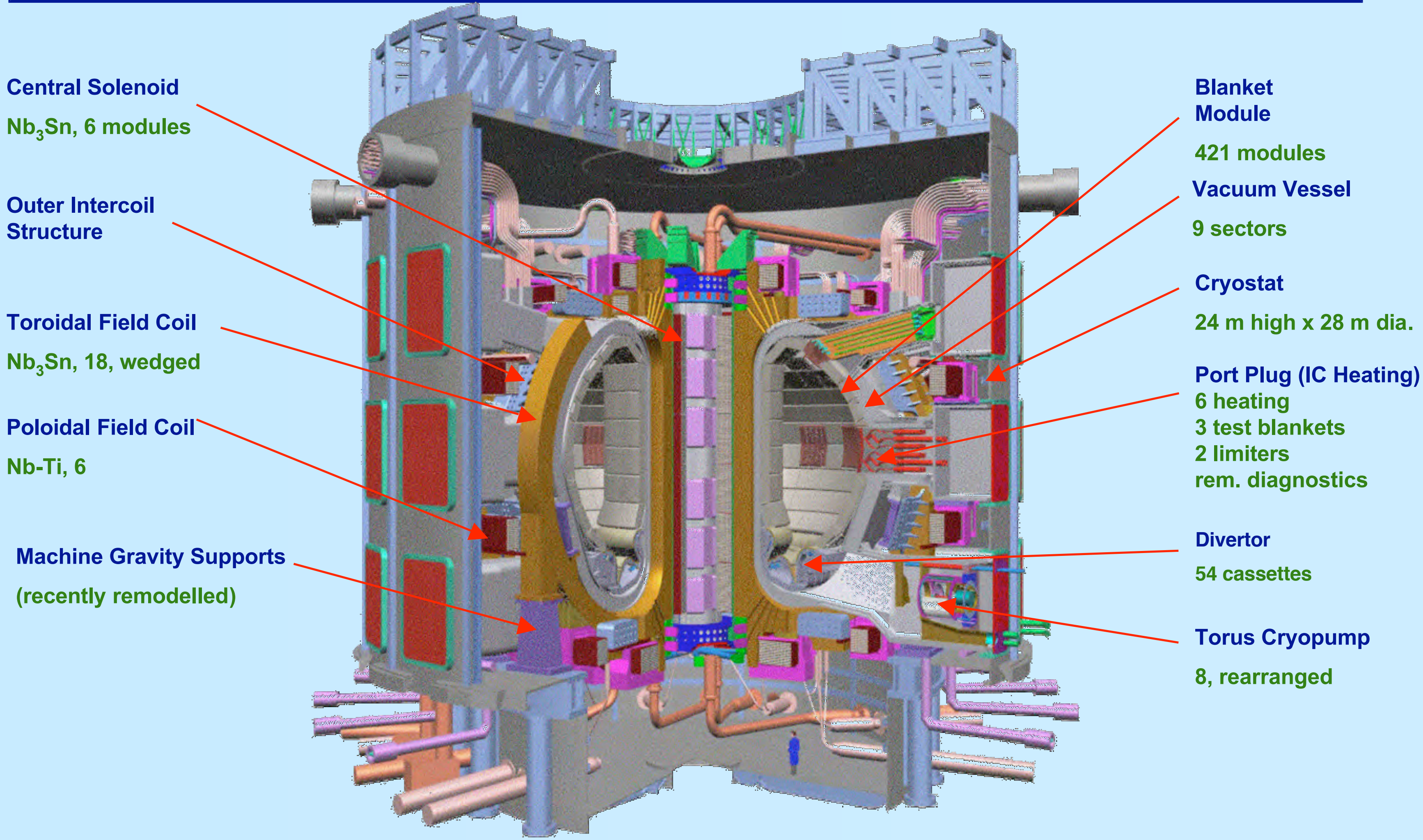
- Moderate Q, extended DT burning plasma, steady state ultimate goal.
- Reactor-essential technologies in system integrating appropriate physics and technology.
- Test high-heat-flux and nuclear components.
- Demonstrate safety and environmental acceptability of fusion.

Strategic

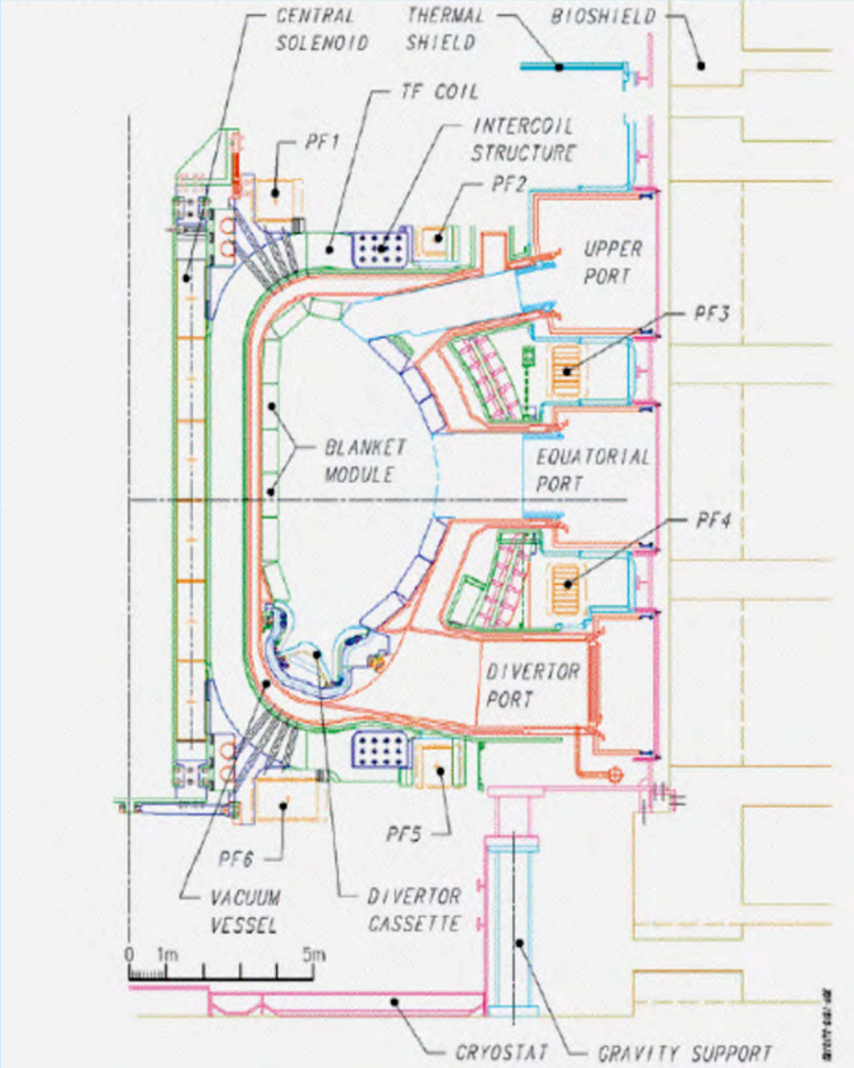
- Single device answering, in an integrated way, all feasibility issues needed to define a subsequent demonstration fusion power plant (DEMO) except for material developments to provide low activation and larger 14 MeV neutron resistance for in-vessel components

Device with $Q \geq 10$ and inductive burn of ≥ 300 s, aiming at steady state operation with $Q \geq 5$, with average neutron wall load ≥ 0.5 MW/m^2 and average lifetime fluence of ≥ 0.3 MWa/m^2.

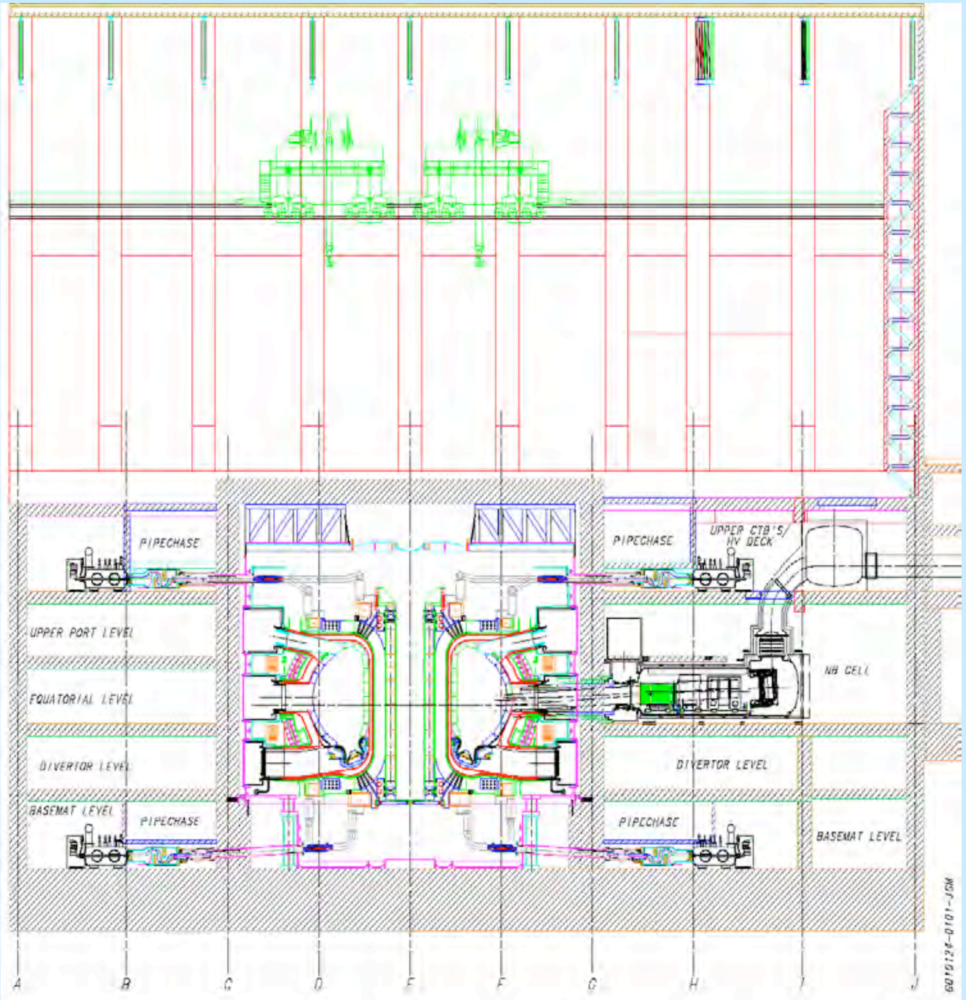
ITER Design - Main Features



ITER tokamak vertical cross-section



ITER Design - Tokamak Building

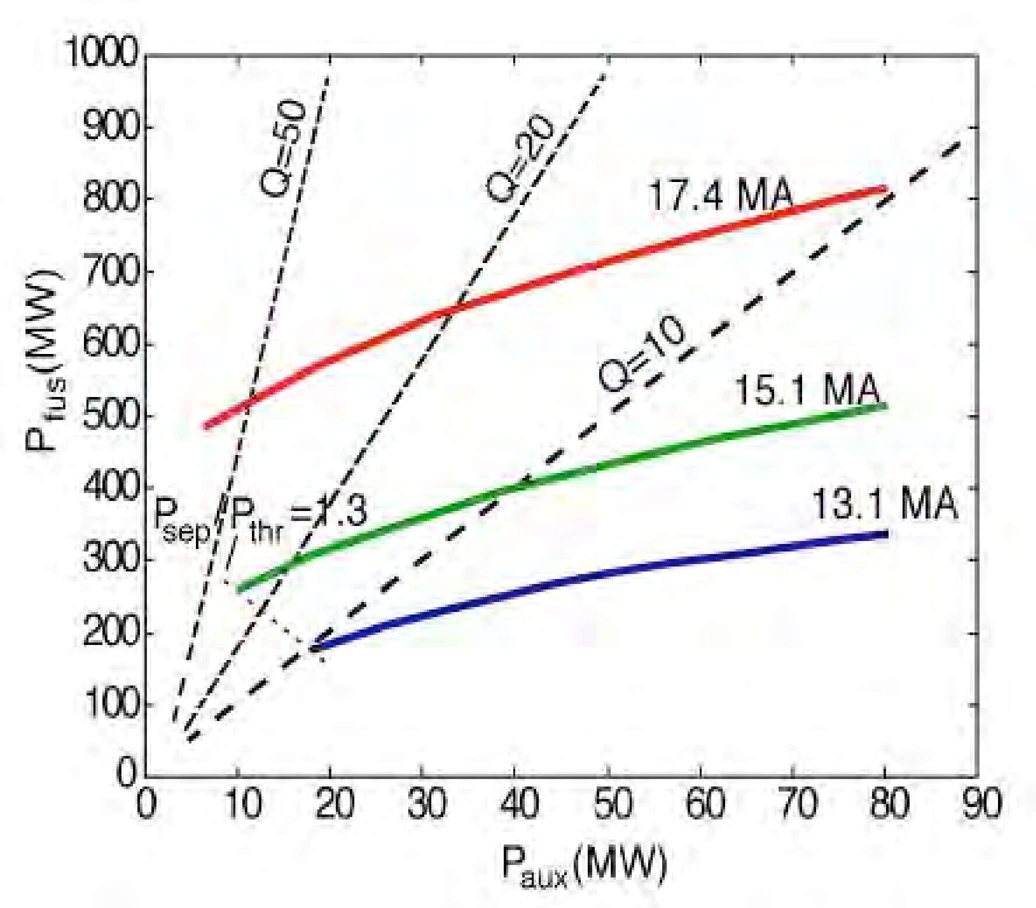


- **Provides a biological shield** around cryostat to minimise activation and permit human access.
- **Additional confinement barrier** against Tritium leak.
- Allows (with HVAC) **contamination spread to be controlled.**
- Provides shielding during remote handling cask transport.
- Can be seismically isolated.

ITER Nominal Parameters

Total fusion power	**500 MW (700MW)**
Q = fusion power/auxiliary heating power	≥10 (inductive)
Average neutron wall loading	0.57 MW/m^2 (0.8 MW/m^2)
Plasma inductive burn time	≥ 300 s
Plasma major radius	**6.2 m**
Plasma minor radius	**2.0 m**
Plasma current (inductive, I_p)	**15 MA (17.4 MA)**
Vertical elongation @95% flux surface/separatrix	1.70/1.85
Triangularity @95% flux surface/separatrix	0.33/0.49
Safety factor @95% flux surface	3.0
Toroidal field @ 6.2 m radius	**5.3 T**
Plasma volume	**837 m^3**
Plasma surface	678 m^2
Installed auxiliary heating/current drive power	73 MW (100 MW)

ITER Inductive Performance



H_H = 1

n_e/n_G = 0.85

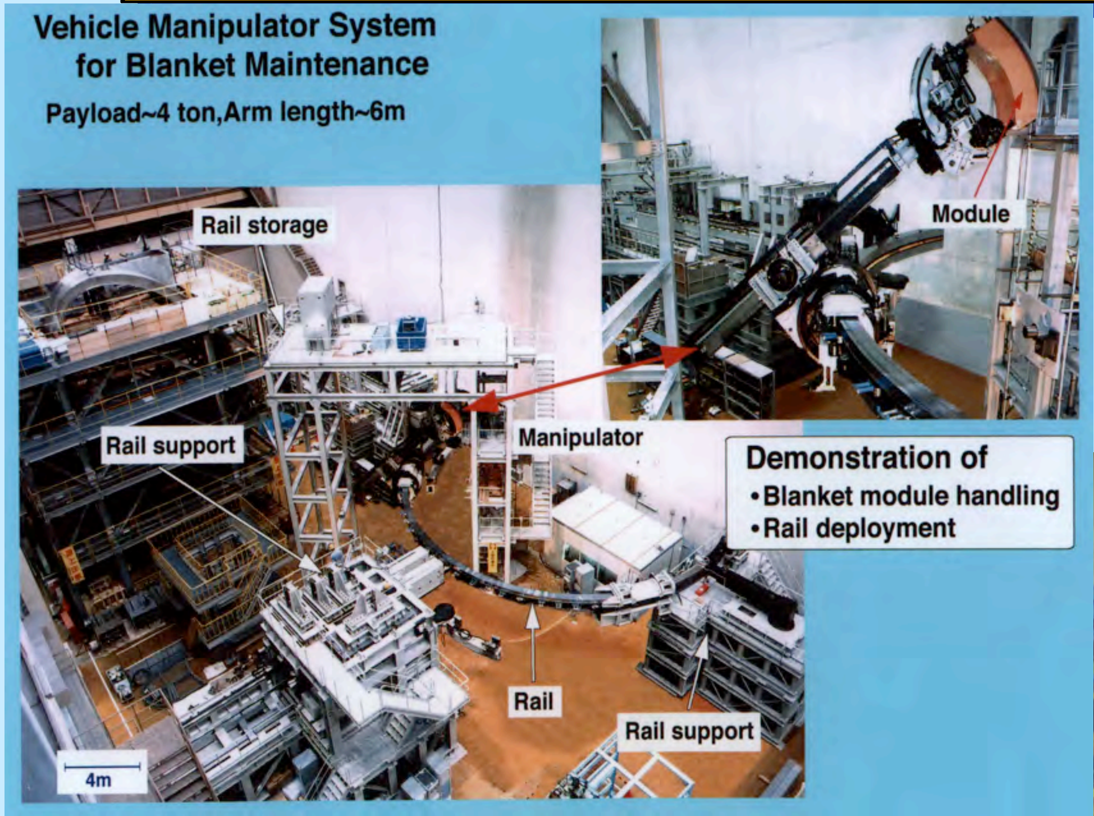
Underpinning R&D for ITER

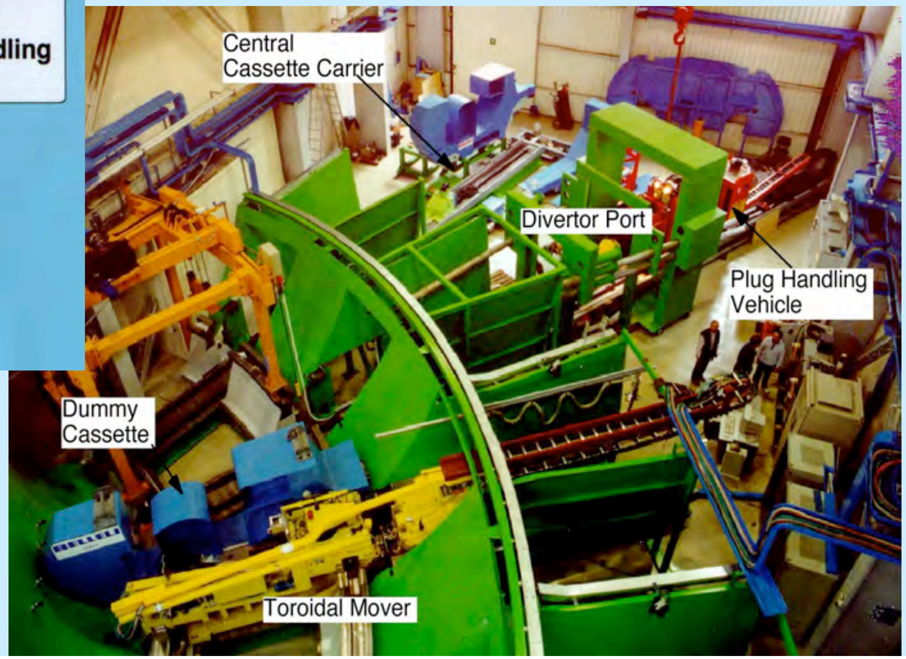
- The ITER design uses established design and manufacturing approaches and validates their application to ITER through technology R&D, **including fabrication and testing of full scale or scalable models of key components, as well as generation of underlying design validation data.**

- **Seven Large R&D Projects were established for the basic machine:**
  - central solenoid and toroidal field model coils
  - vacuum vessel sector, blanket module, and divertor cassette
  - blanket and divertor remote handling

- Other R&D concerned safety-related issues, and auxiliary systems - heating and current drive, fuelling and pumping, tritium processing, power supplies and diagnostics, etc.

Design Feasibility - Maintenance





ITER Safety and Environmental Characteristics

- **One of the main ITER goals is to demonstrate the safety and environmental advantages of fusion:**
  - low fuel inventory, ease of burn termination, self-limiting power level
  - low power and energy densities, large heat transfer surfaces and heat sinks
  - confinement barriers anyway exist and need to be leak-tight for operation
- **Environmental impact**
  - potential dose to most exposed member of public is < 1% background under normal operation
  - under worst accidents, dose to most exposed member of the public would be similar to background
  - even under hypothetical (i.e not accident sequence driven) internal events, no technical need for public evacuation.
- **Waste**
  - about 30,000 t of material will be radioactive at shutdown. 24,000 t of this can be cleared (without reprocessing) for re-use within 100 years.
- **Worker Safety**
  - assessment of all major system maintenance procedures demonstrates low occupational exposure, and this is being further refined as part of the project's ALARA policy.

ITER Construction Valuation Method

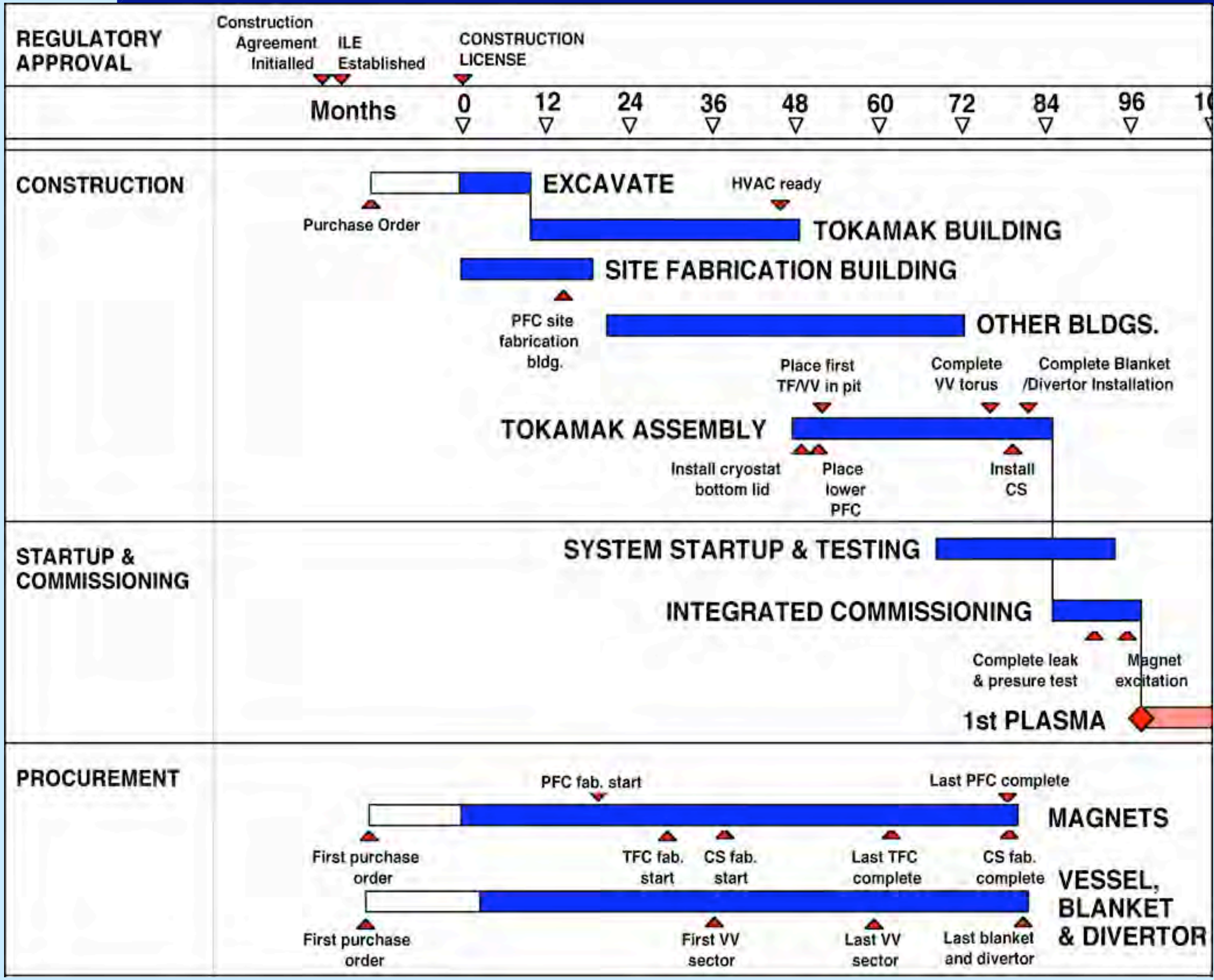
- Construction broken into 85 procurement packages representative of actual contracts - half inside the ‘pit’, rest for peripheral equipment.
- Industry and large laboratories with relevant experience analysed manufacturing and estimated manpower, materials, tooling, etc. for given delivery schedule.
- Estimates consolidated by using a single set of labour rates and material costs on all packages.
- **Since many items contributed “in kind”, actual cost to each participant may not correspond to the value to the project of what is delivered, but partners for ITER construction can agree collectively on the relative value of different procurement, and therefore on each individual percentage share of the construction cost.**
- To eliminate currency/inflation fluctuations, all valuations made in 1989 US $.

ITER Lifetime Cost

	kIUA*
Construction Costs	
Direct Capital	2755
Management & Support	477
R&D During Construction	~70
Operation Costs (average per year)	
Permanent Personnel	60
Energy	~30
Fuel	~8
Maintenance Improvements	~90
Decommissioning **(without long-term storage of activated components)**	335

1 kIUA = $\$_{1989}$1M≈ $\$_{2000}$1.392M ≈ €$_{2000}$1,279M ≈ ¥148M

ITER Construction Schedule



- 7 year construction
- 1 year integrated commissioning
- ILE (ITER Legal Entity) established about 2 years before award of construction license
- Long lead item calls for tender sent out and procurement started before license awarded
- Success-oriented schedule

Conclusions

- **The need for a burning plasma experiment** at the centre of the fusion development **strategy is undisputed**.
- **There is consensus that it will reach its objectives** and **"the world fusion programme is scientifically and technically ready to take the important ITER step".**
- The success of the EDA demonstrates feasibility and underlines the desirability of jointly implementing ITER in a broad-based international collaborative frame: it supports the Parties' declared policy to **pursue the development of fusion through international collaboration.**
- Negotiations between six parties (EU, China, JA , Korea, RF, US) on an agreement for joint construction and operation of ITER started in 2001, progressing until the end of 2003 in defining all aspects except in the site choice. From then, competition between two possible sites, in Japan and Europe/France has led to delays; now on the verge of being resolved (July 2005?)

Therefore, it is safe to say that nuclear fusion is alive and well!
The potential for energy generation is real.