CERN Colloquium

Controlled Nuclear Fusion by Magnetic Confinement and ITER

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CERN

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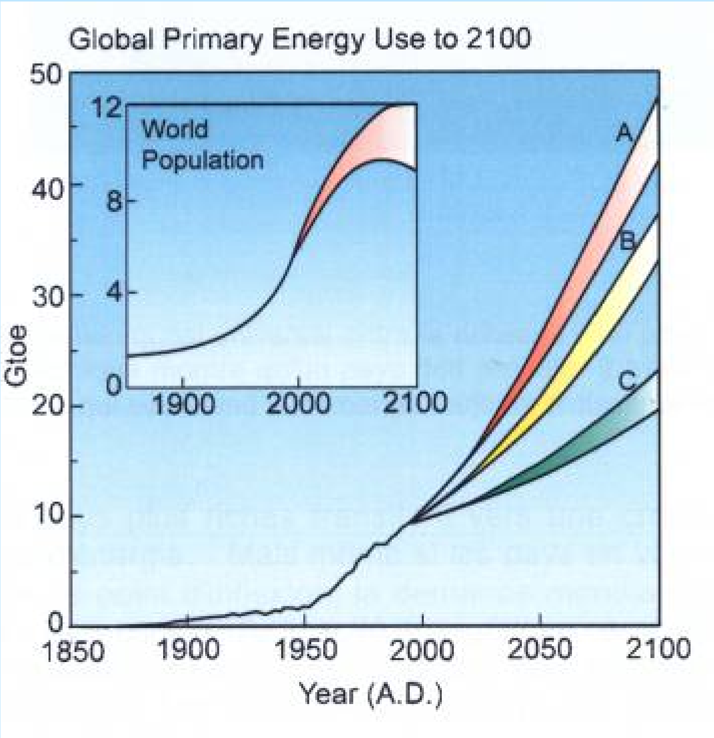
There is a popular view that fusion energy has been just over the horizon for decades, and that it has failed to deliver.

This is false!

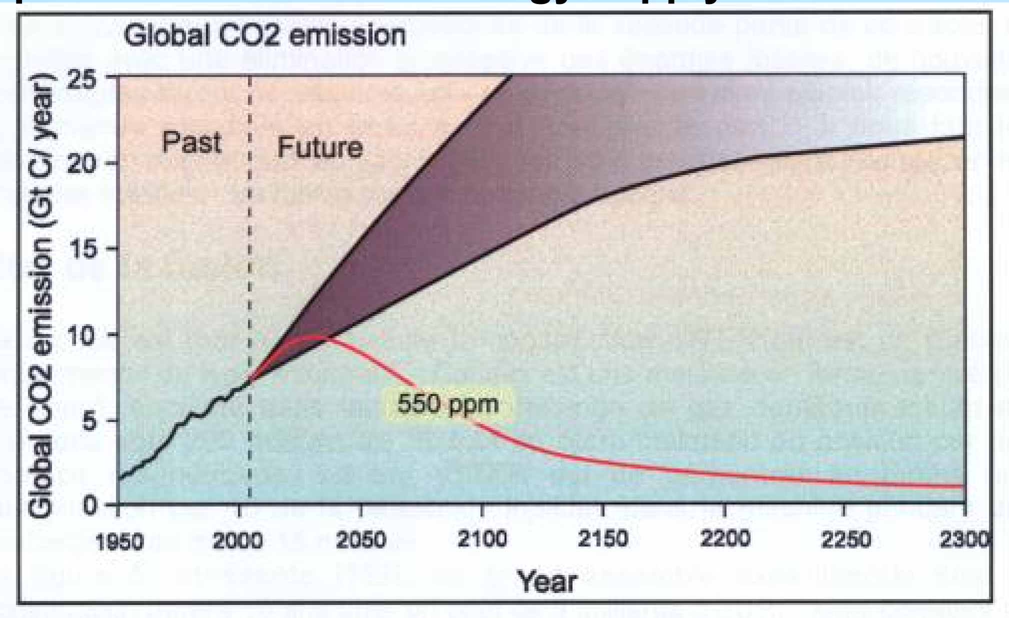
Fusion has always been a long-term project.

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

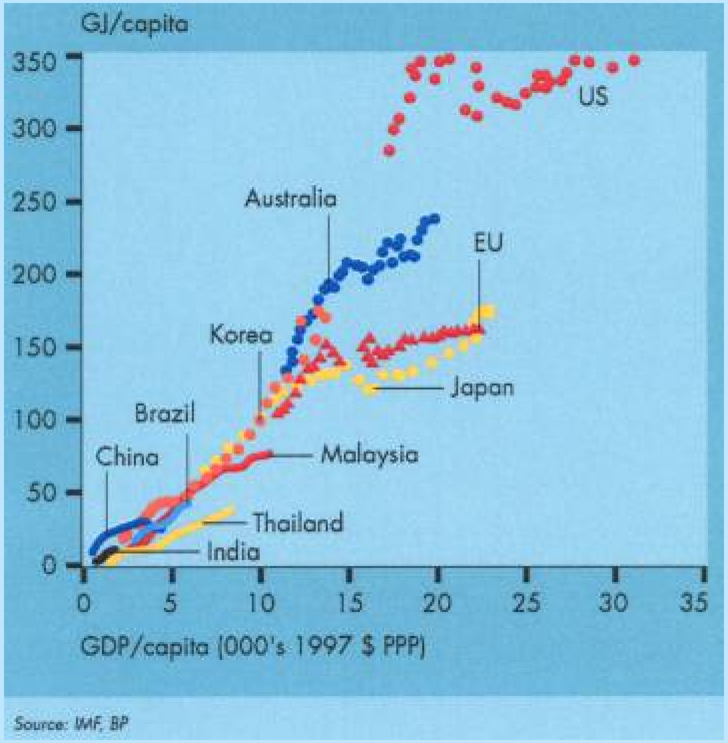


The projected increase in the world's population is accompanied by a dramatic increase in energy consumption.
Scenarios A, B and C correspond to high growth, a middle course, and an ecologically-driven global energy policy.
All require new sources of energy supply.

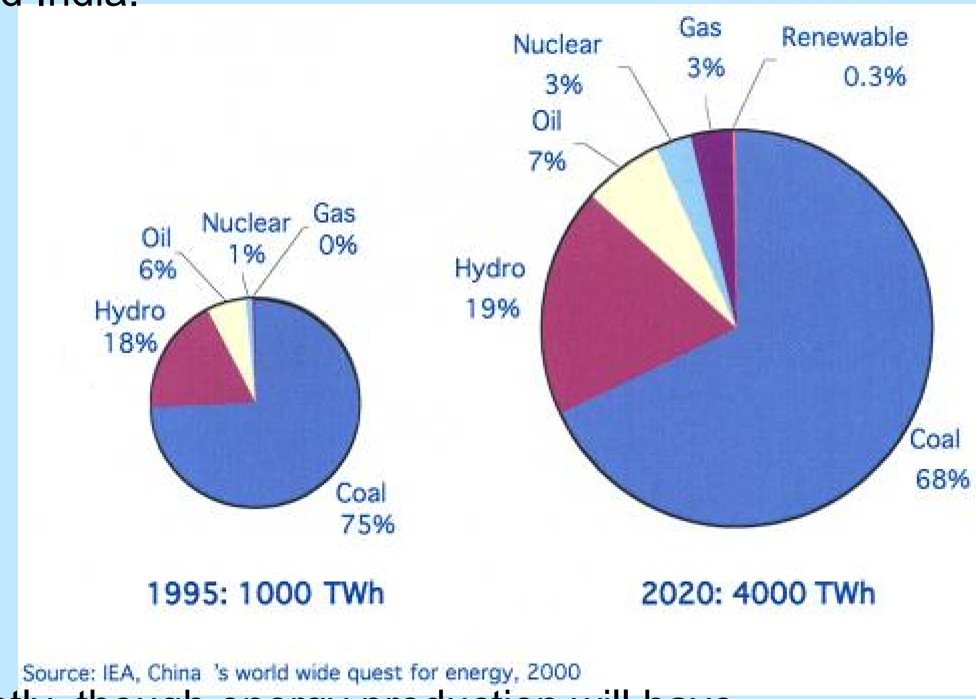


Projections based on current energy supply, enclosed within the black lines, do not allow atmospheric CO2 concentrations to be controlled.
To stabilise at 550ppm, emissions must soon start to fall dramatically (red line).
This can only be achieved with an energy supply that emits zero greenhouse gas.

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 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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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
  - $4\ {}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\ \nu_e + 26.7$ 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 :**
  - $\mathbf{{}^{2}D + {}^{3}T \rightarrow {}^{4}He\ (3{,}5\ MeV) + {}^{1}n\ (14{,}1\ MeV)}$
  - $6\ L_i + {}^{1}n \rightarrow {}^{3}T + {}^{4}He$ (+ 4,8 MeV)
  - $7\ L_i + {}^{1}n \rightarrow {}^{3}T + {}^{4}He + {}^{1}n$ (– 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

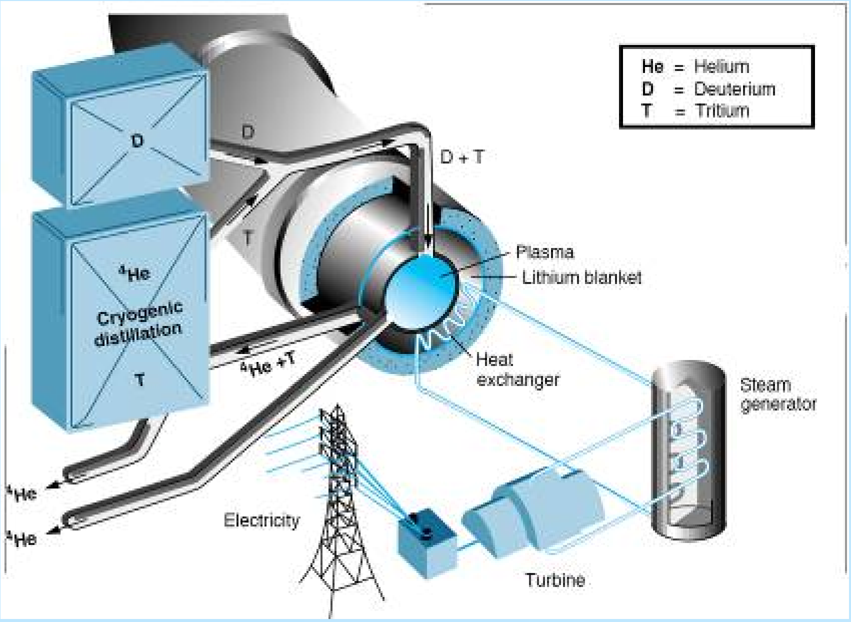
keep them together for long enough

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 ^{4}He produced (20% of the fusion power) remains in the plasma and stabilises the temperature T against power losses
    - o ^{1}n 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:**



$$\frac{1}{4}n^2R(T)\frac{E_F}{5}\left(1+\frac{5}{Q}\right)\geq\frac{3nT}{\tau_E}$$

fusion power — auxiliary power — 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

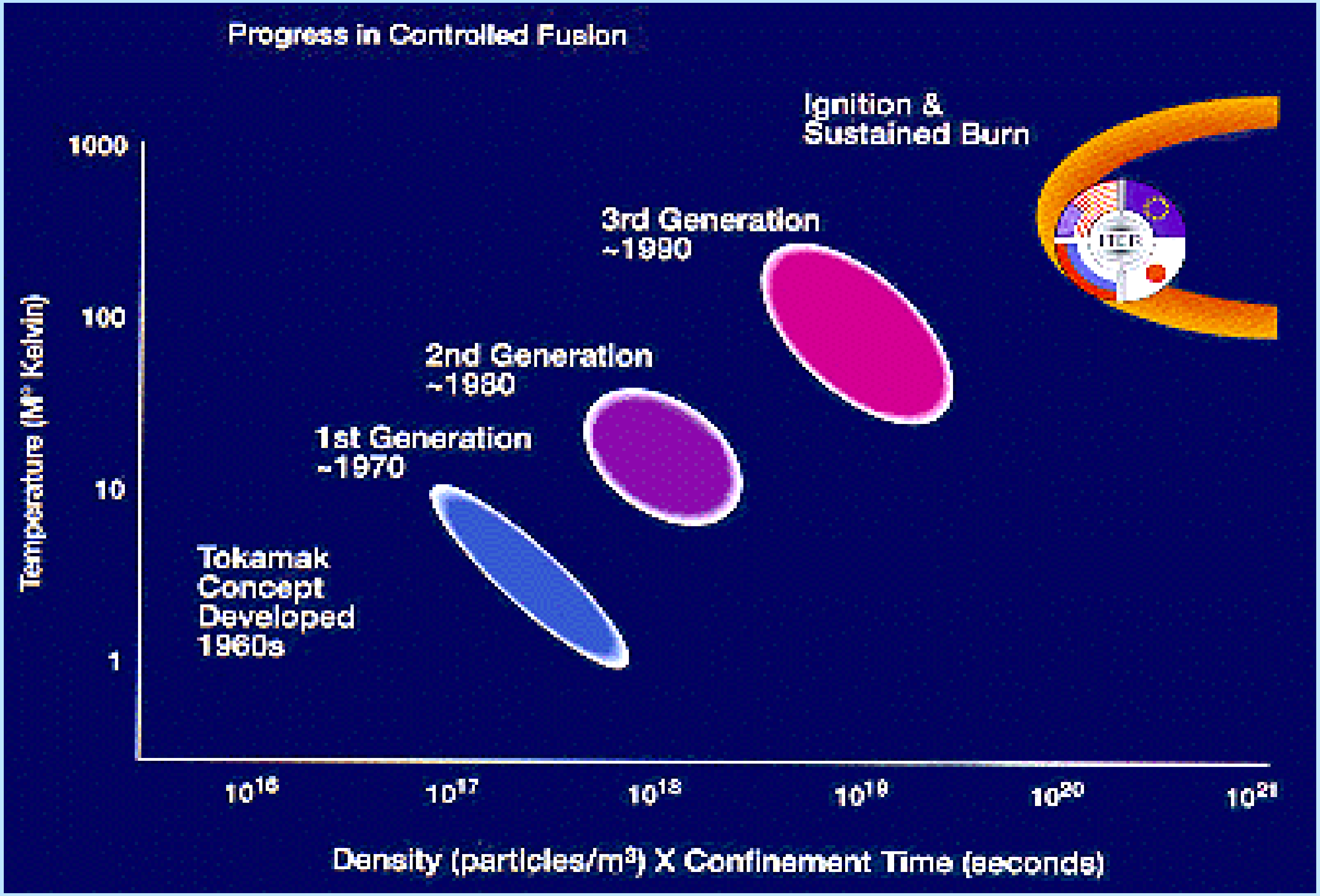
R(T) reaction rate

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

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

$$\boxed{n\tau_E T\geq \text{ minimum for T } \approx 1.5\times10^8\mathrm{K}}$$

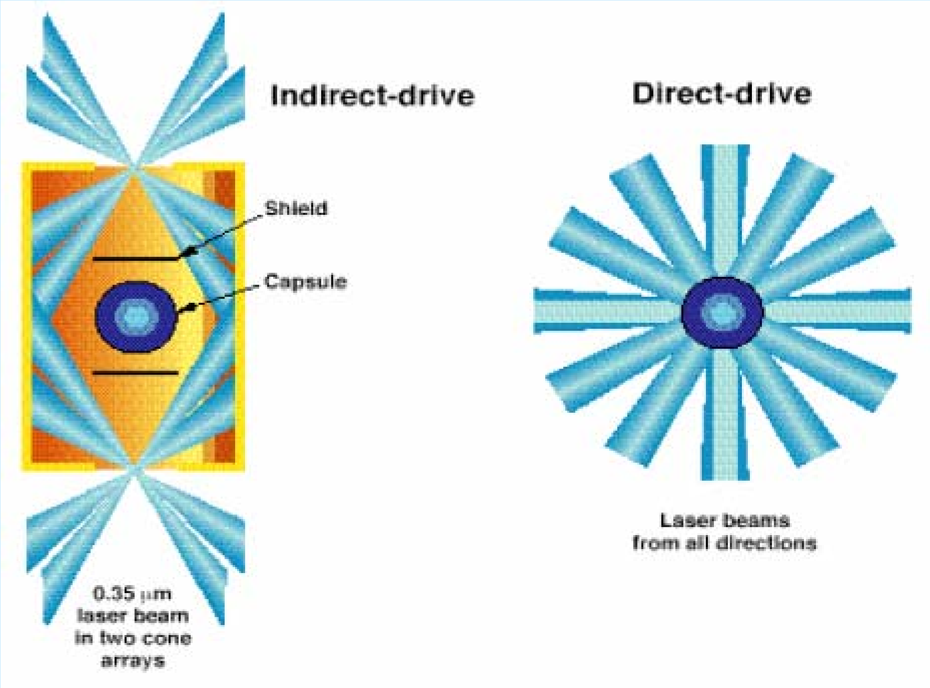
Progress in fusion research



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

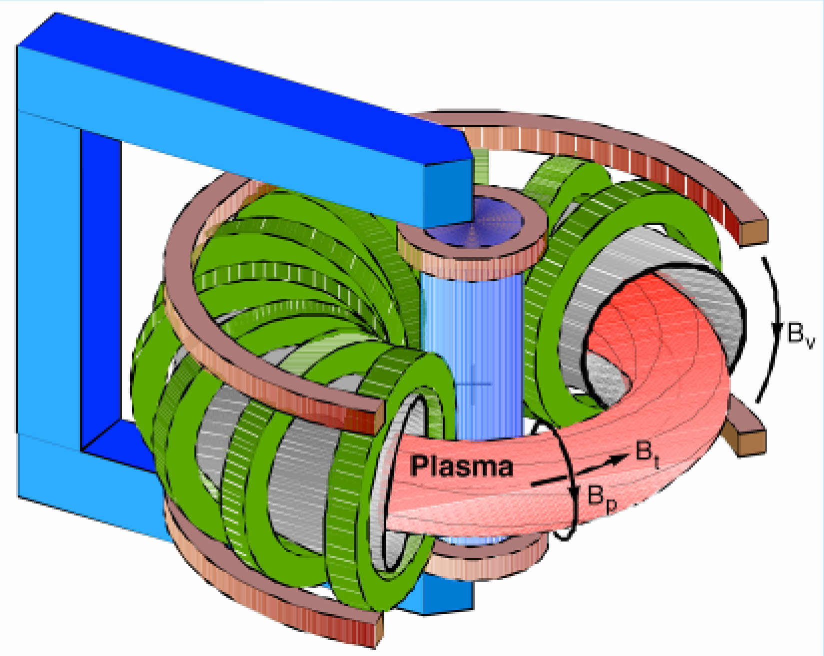


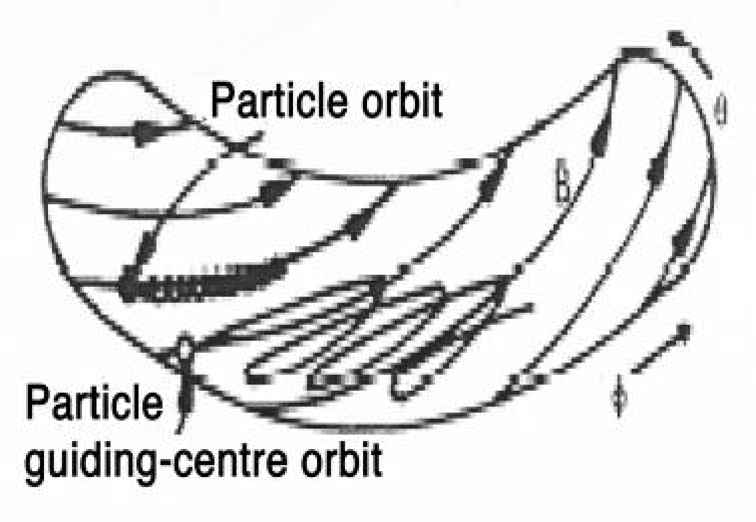
$$G = \frac{E_{Fusion}}{E_{input}}$$ large enough $\geq$ 50 - 100

$$n\,\tau_E T \geq \frac{T}{R(T)}$$ **the minimum is obtained for T $\simeq 3 \times 10^8$ K**

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

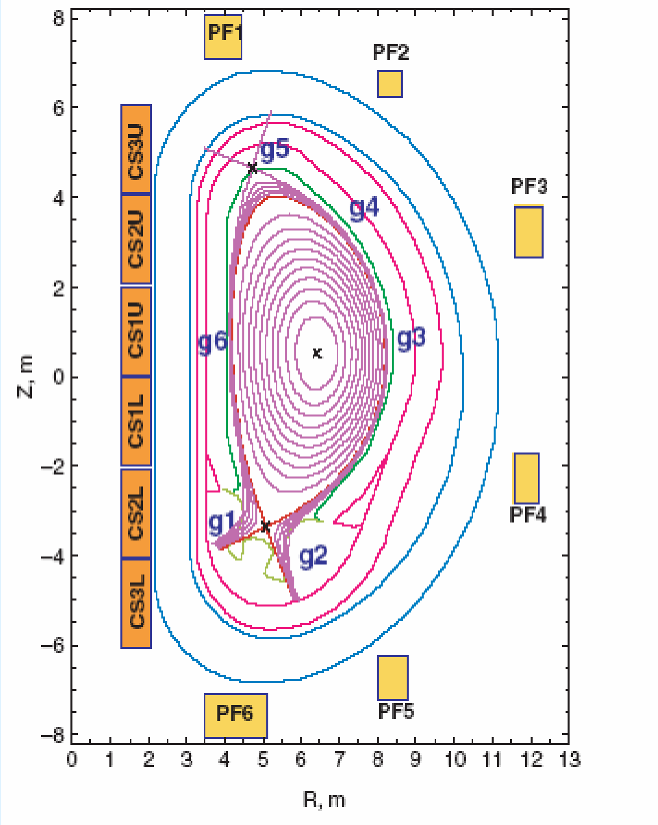
- **single particles are confined** in the torus, as long as there is a **rotational transformation in the topology of the magnetic lines:** a poloidal magnetic field (due to toroidal plasma current) added to a larger toroidal component
- **The particle motion is periodic** (3 frequencies associated)





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, but **n = I / a²**
   - ∇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.)

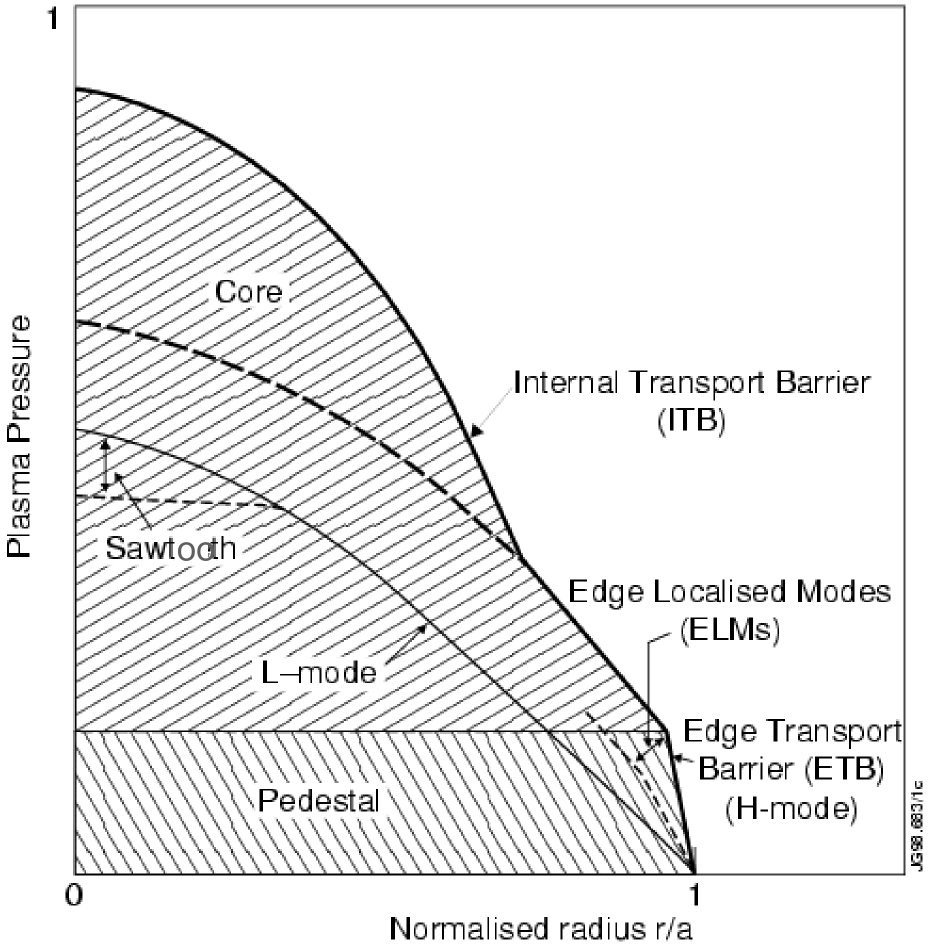
This empirical method received support principally by successfully confronting it with **relations built from non-dimensional parameters** (a kind of "wind tunnel" analysis).

$$\omega_{\mathrm{ci}}\tau_{\mathrm{E}} \approx \rho_*^{-3}\beta^0\nu_*^{-0.35} \quad \text{with} \quad \rho_* = \frac{\rho_{\mathrm{ion}}}{\mathrm{a}},\ \nu_* = \frac{\nu_{\mathrm{collision}}}{\nu_{\mathrm{period}}},\ \beta$$

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.**

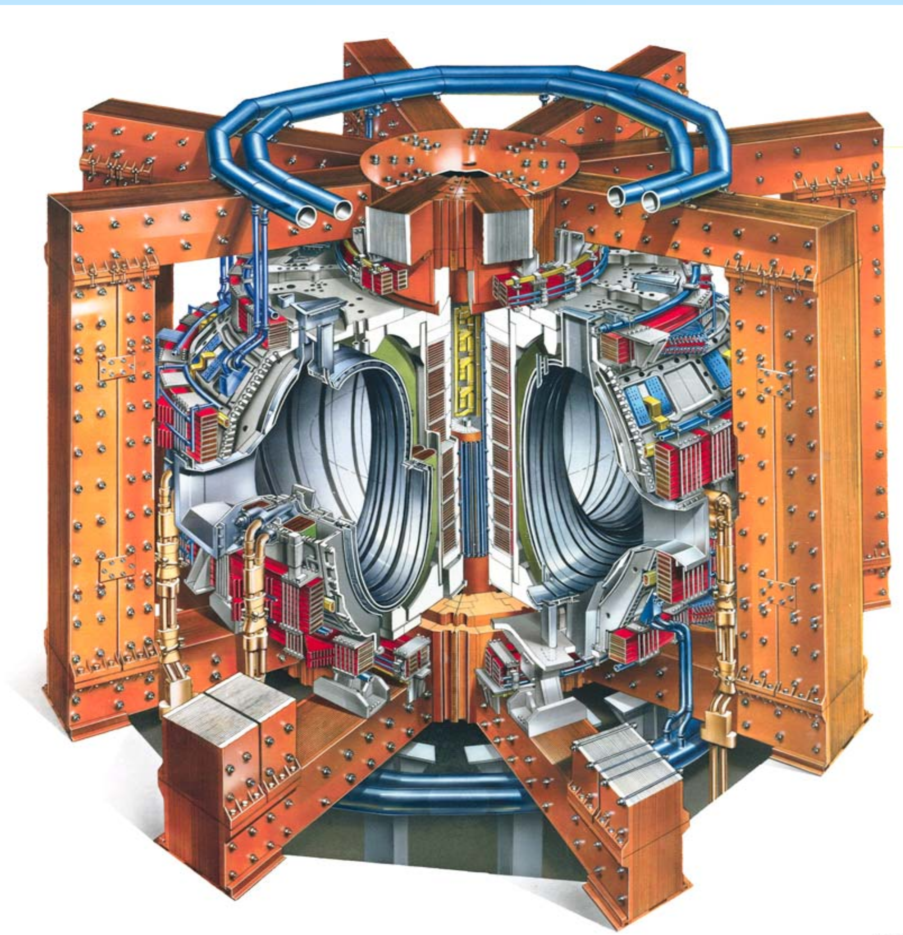


Relations with other physics domains

- 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

The Joint European Torus (JET)



Plasma operation closest to ITER

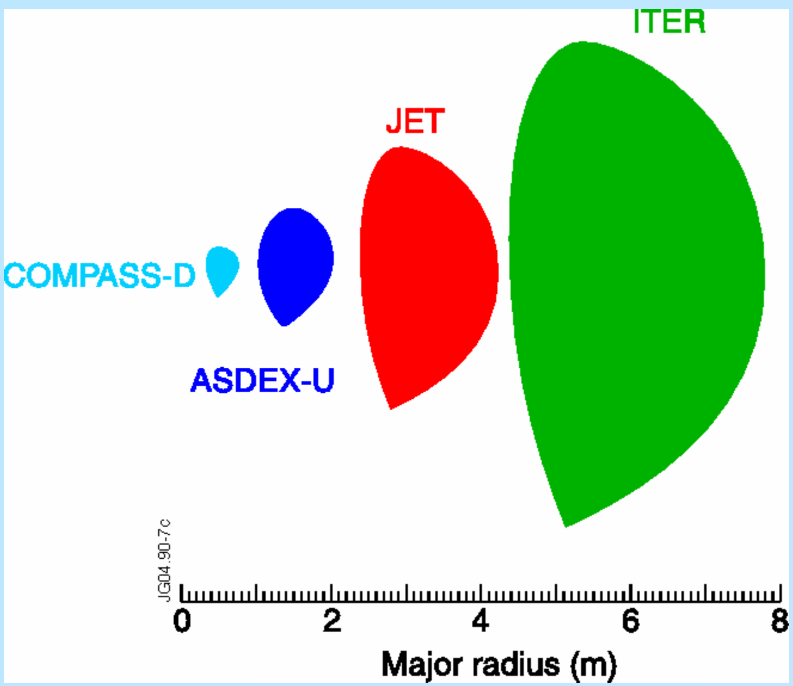
Torus radius	**3.1 m** ***(ITER 6m)***
Vacuum vessel	**3.96m high x 2.4m wide**
Plasma volume	**80 m^3 - 100 m^3**
Plasma current	**up to 5 MA** ***(ITER 17MA)*** **in present configurations**
Main confining field	**up to 4 Tesla**

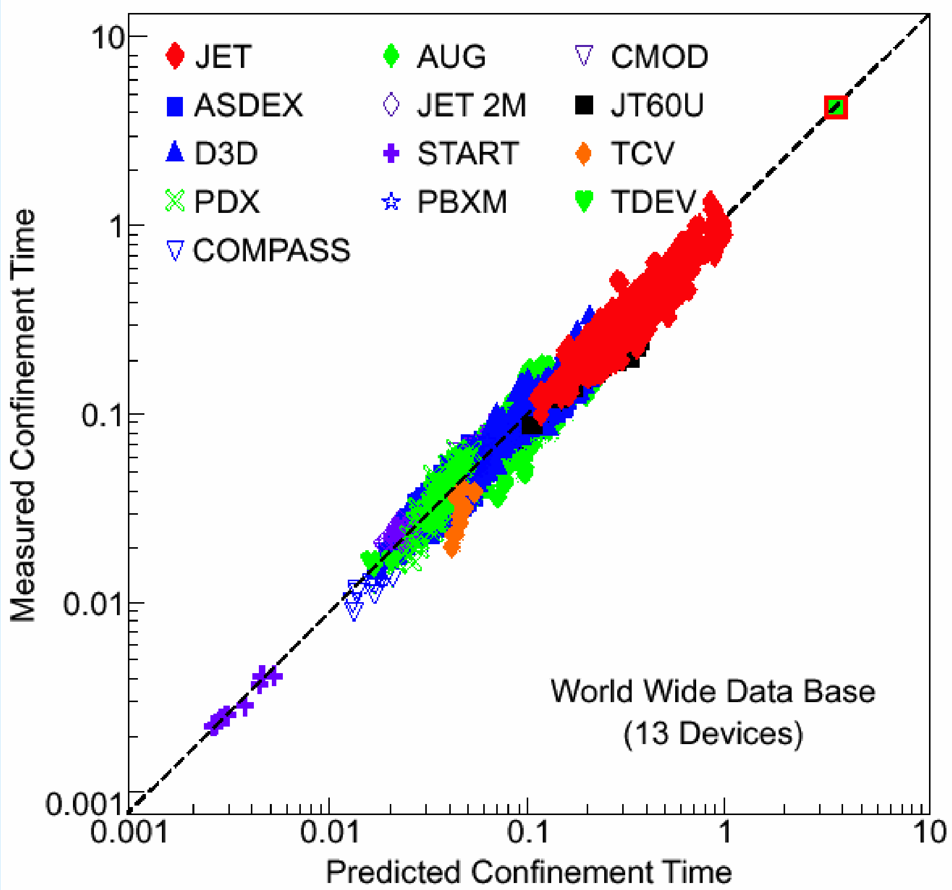
Unique technical capabilities worldwide:

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

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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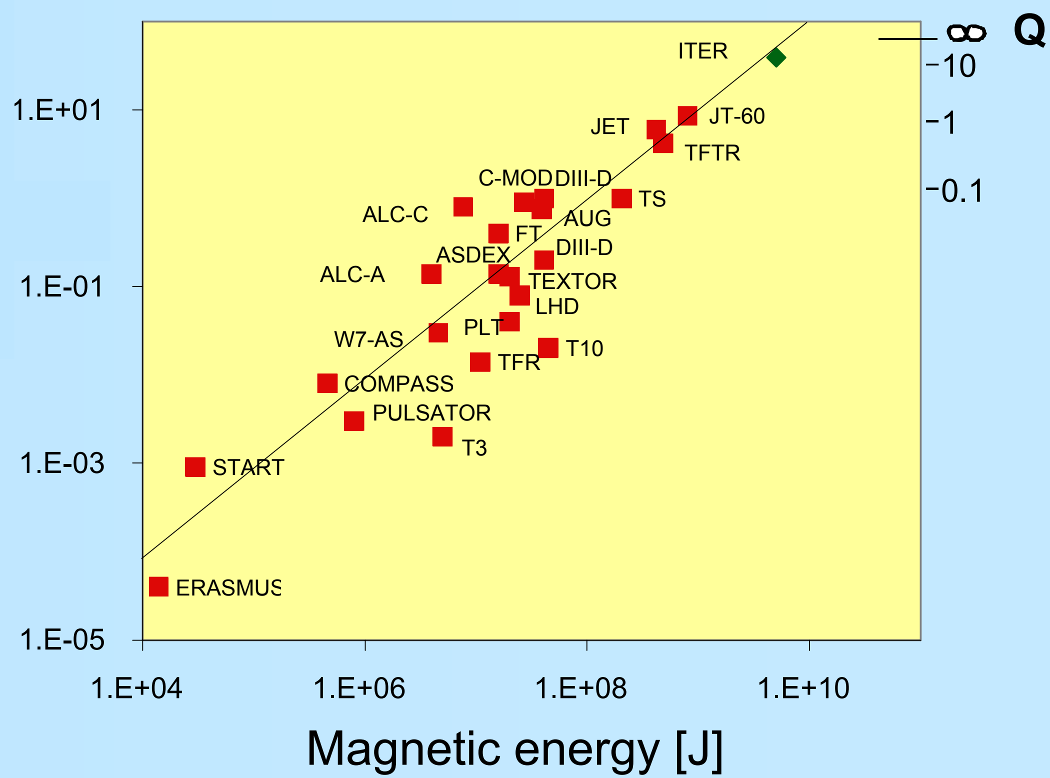
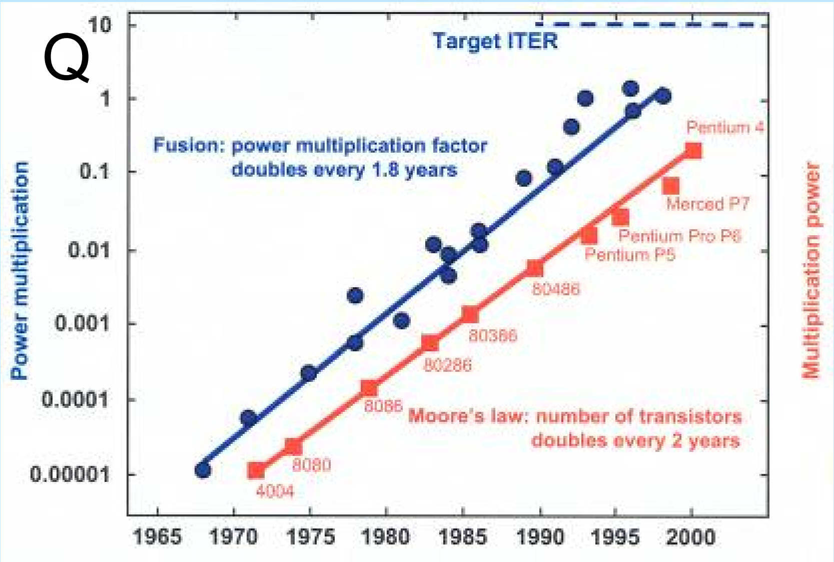
Why ITER? Why now?
Past achieved plasma performances

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





$n\tau T$ 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

Present Generation of Large Tokamaks

JT-60
JET
TFTR

Physics basis for extrapolations and predictions of performances of next step machines

Experimental Reactor

ITER

Demonstration of Technologies essential for a power reactor
- Superconducting coils
- Plasma power and particle exhaust component
- Remote maintenance
- Reactor-relevant tritium-breeding blankets

Confirmation of physics basis
- confinement
- alpha particle physics
- steady state operation

Demonstration Reactor

DEMO

Optimisation of Tokamak Reactor Design
Availability of Electrical Power
Evaluation of Economics

Commercial Power Reactor

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.

Why ITER?

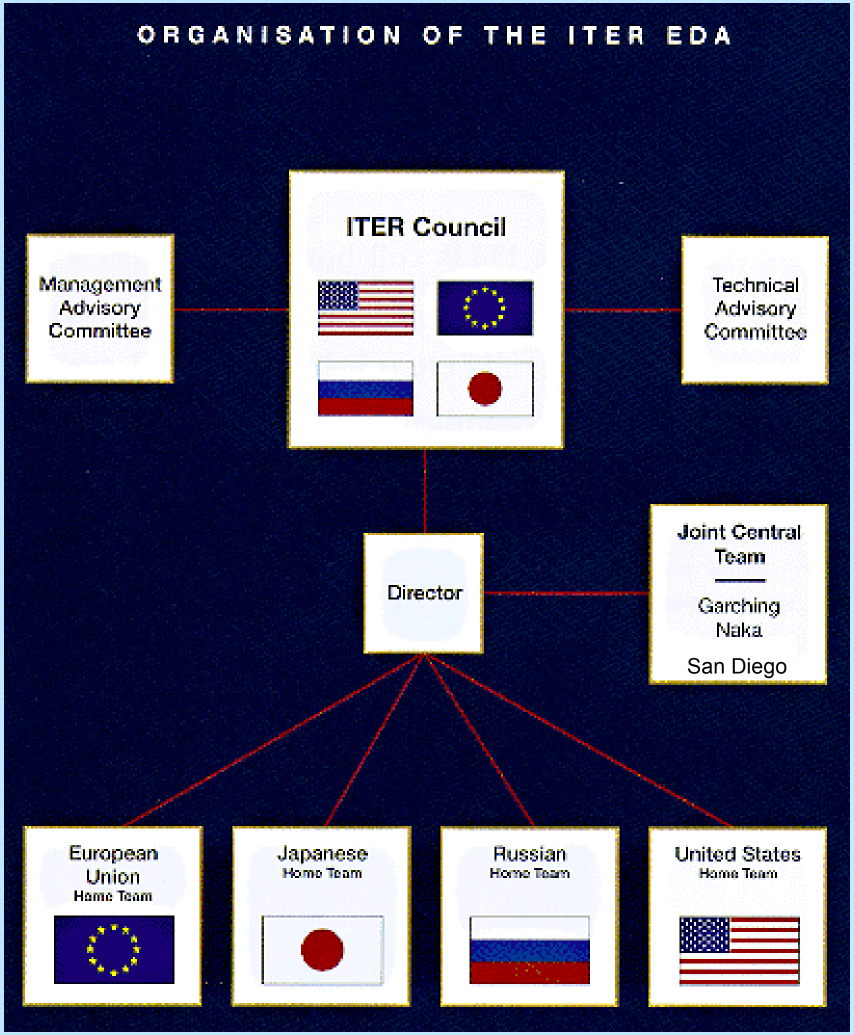
The present experiments are able to simulate (not necessarily simultaneously) most plasma parameters β, ν, n, T, j, B which control the plasma performance, all of them being relevant to a power reactor.

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.**

International structure of ITER



Role of the Joint Central Team

- **Establish the engineering design of ITER including**

  - a complete description of the device,

  - detailed designs with specifications, calculations, drawing and safety analyses,

  - planning schedule and cost estimates for construction and operation,

  - specifications allowing immediate call for tender for long lead time items

Role of the Home Teams

- **The Parties' Home Teams:**

  - Carry out the validating R&D work required for performing the activities previously described, including development, manufacturing and testing of scaleable models to ensure engineering feasibility,

  - Perform the engineering design of specific ITER components and subsystems

- **Primary ITER/industry interface is through the Home Teams**

Impact of ITER on the Fusion Development Programme

The demanding technical challenges of ITER and its international collaborative nature have led to the breaking of new technical ground in fusion science and engineering.

In addition to the technical results, the project has demanded and enabled new modes of closer programmatic collaboration,

- among physicists, in co-ordinating and collating experiments and results world-wide, and
- among technologists, in pursuing large, multi-Party projects on the key technological aspects of ITER design.

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.

2. What is ITER ?
Design overview of the Device

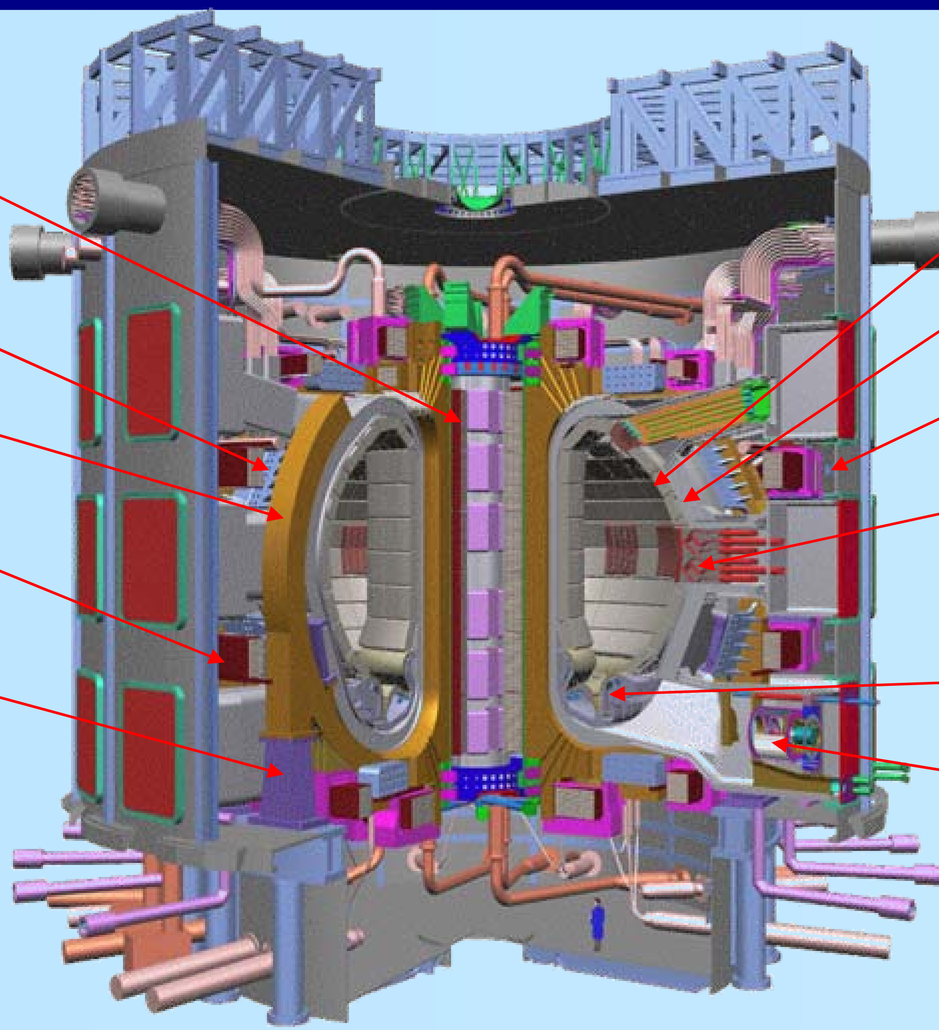
Technical dossier (published by IAEA, ITER series)

- **Summary of ITER Final Design Report (May 2001)**
  (presented by the ITER Director)
- **Technical Basis for the ITER Final Design Report, Cost Review and Safety Analysis (June 2001)**
- **The complete "Final Design Report" includes a comprehensive documentation:**
  - » **Available at the end of EDA**
  - » **Structure expected to remain valid for ITER construction**

Summary in Journals

- – **In Physics:** ***ITER Physics Basis (NF 39 (1999)2137-2664)***
- – **In Technology:** ***R&D results in*** **"Fusion Engineering and Design" (July 2001)**
- – **In Safety:** ***Generic Site Safety Report*** **(Safety Analysis ~ 1000 pages)**

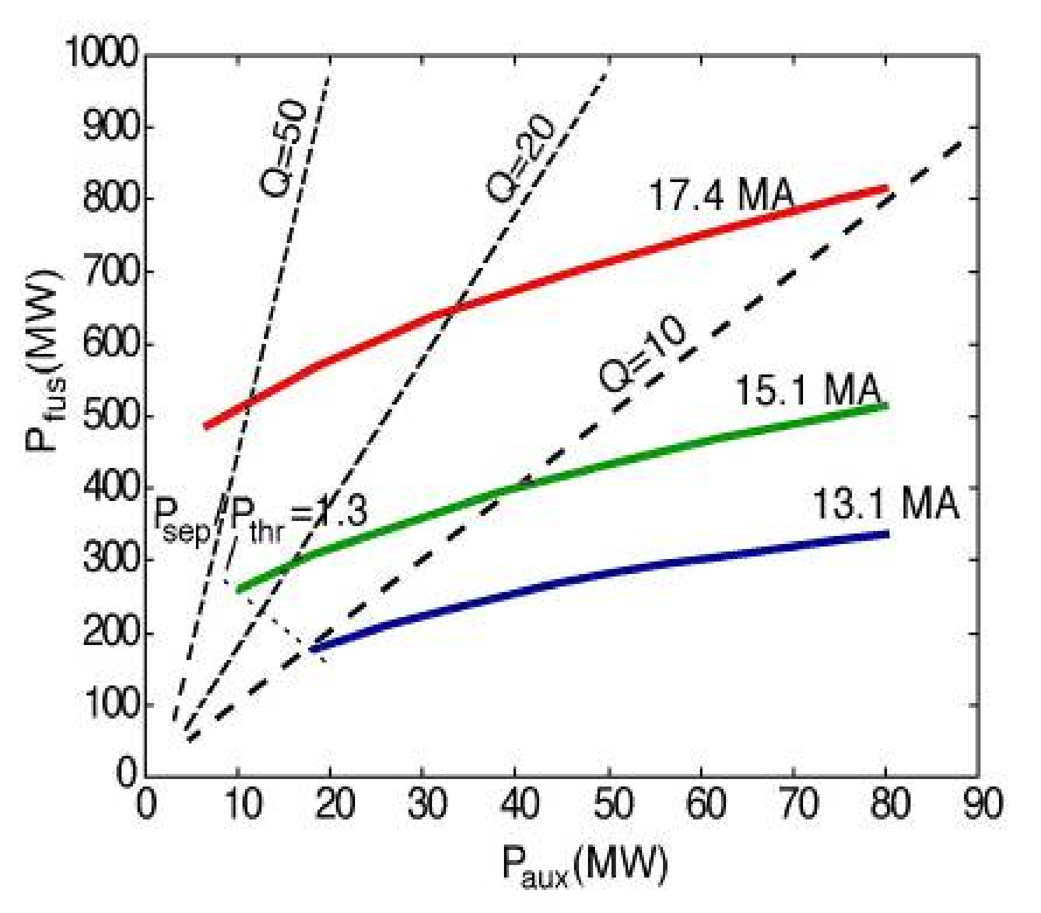
ITER Design - Main Features



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)

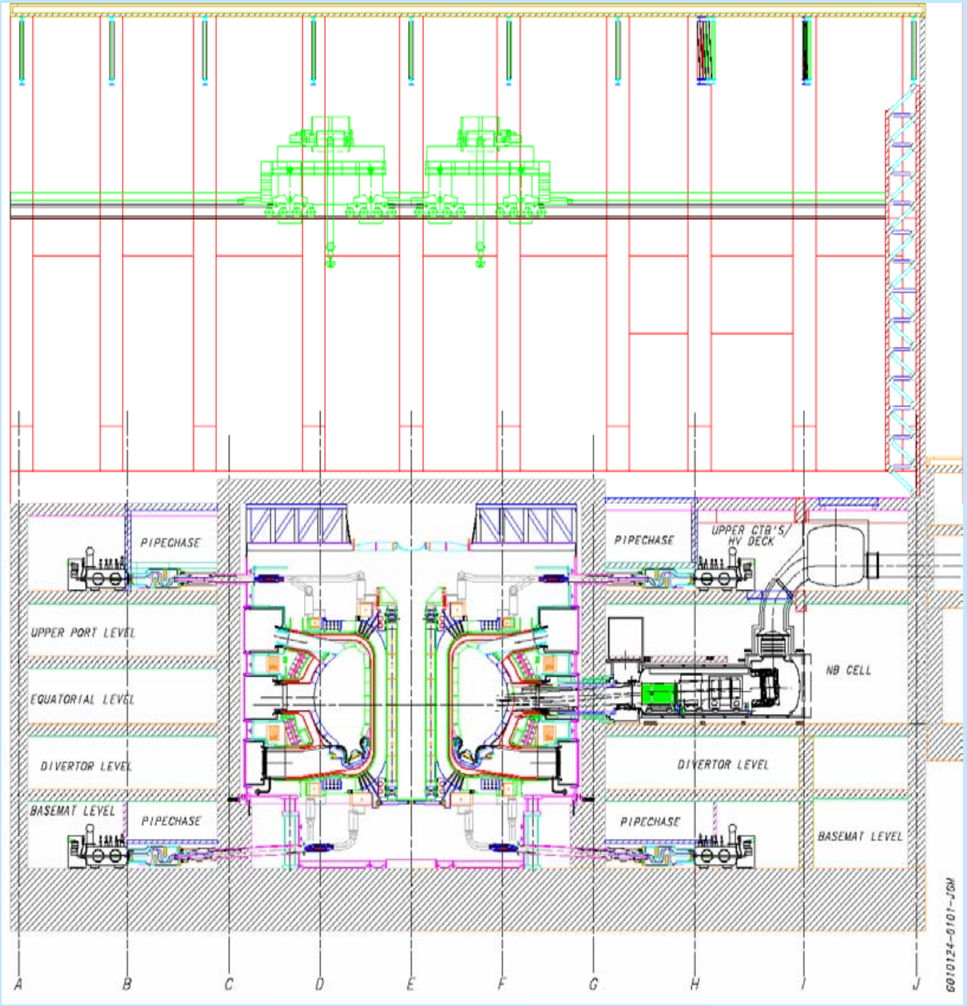
ITER Inductive Performance



$H_H = 1$

$n_e/n_G = 0.85$

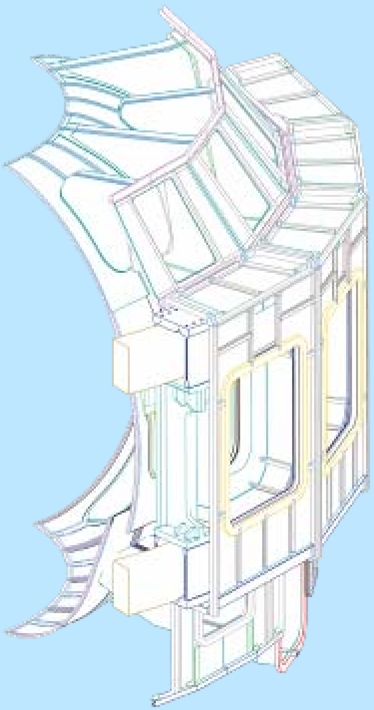
ITER Design - Tokamak Building

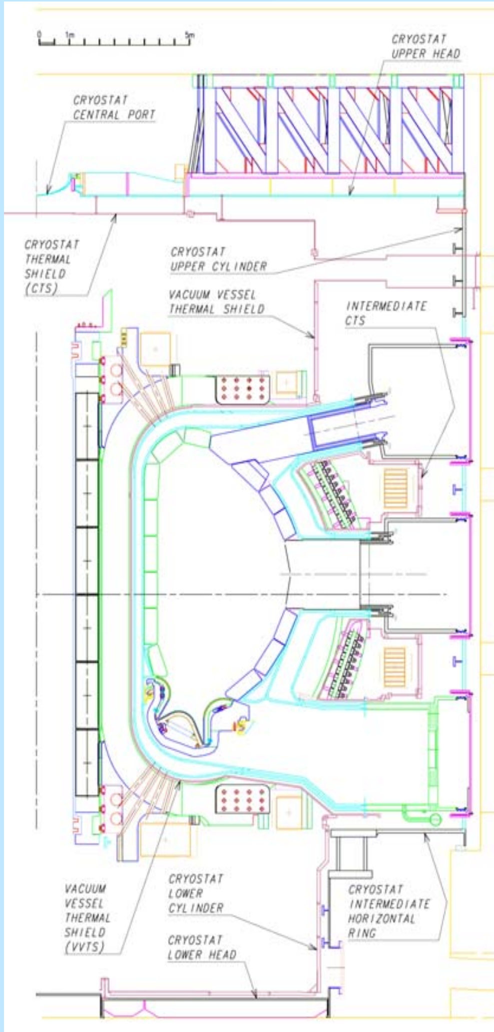


- **Provides a biological shield** around cryostat to minimise activation and permit human access.
- **Additional confinement barrier** against Tritium leak.
- Allows (with HVAC) **contamination spread to be controlled.**
- Provides shielding during remote handling cask transport.
- Can be seismically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

ITER Site Layout

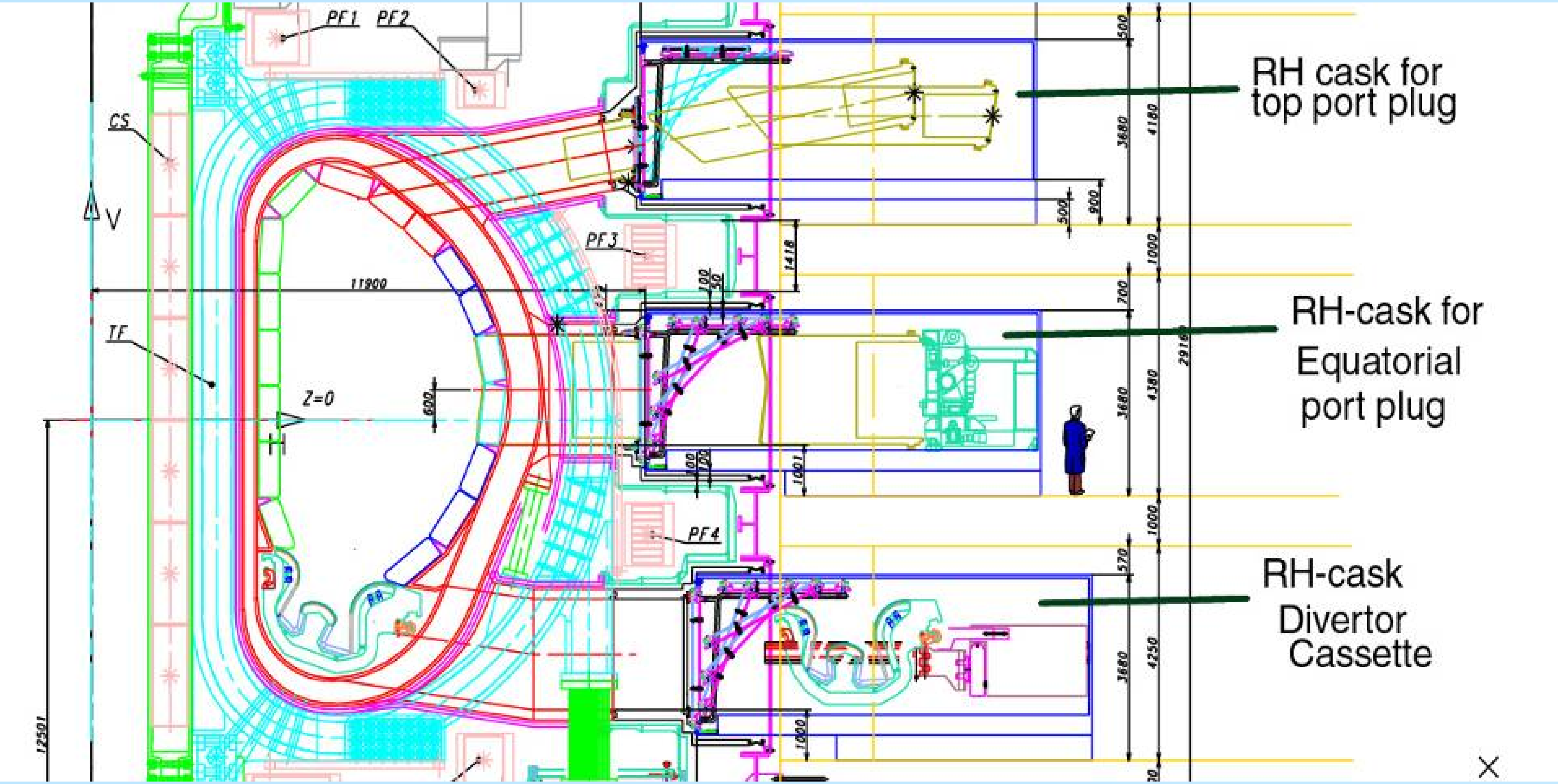
Design - Cryostat & Thermal Shields



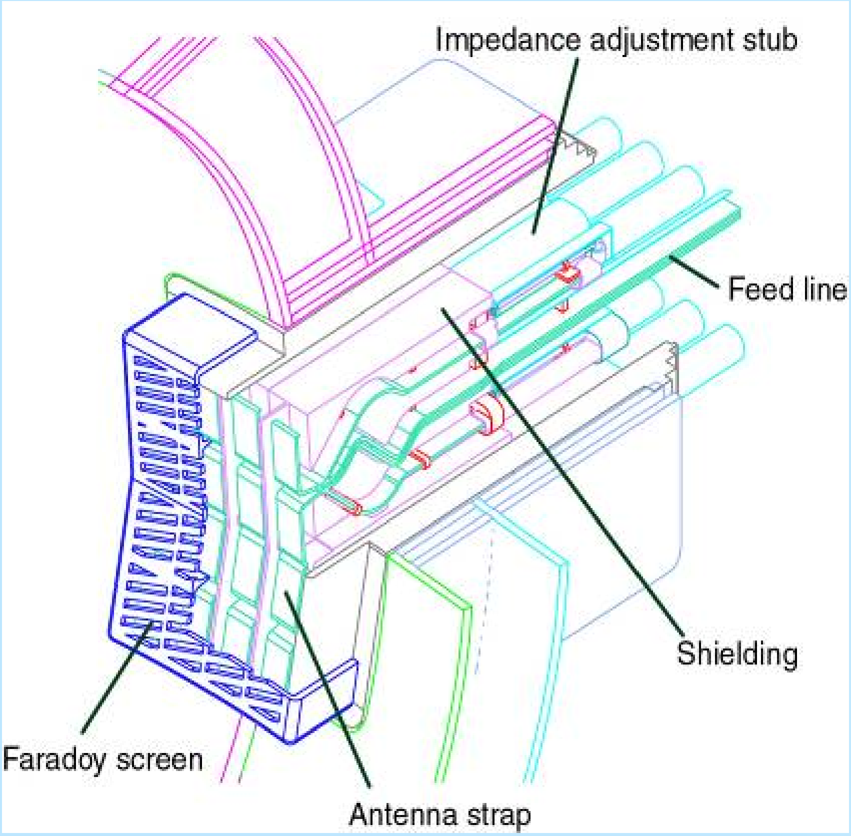


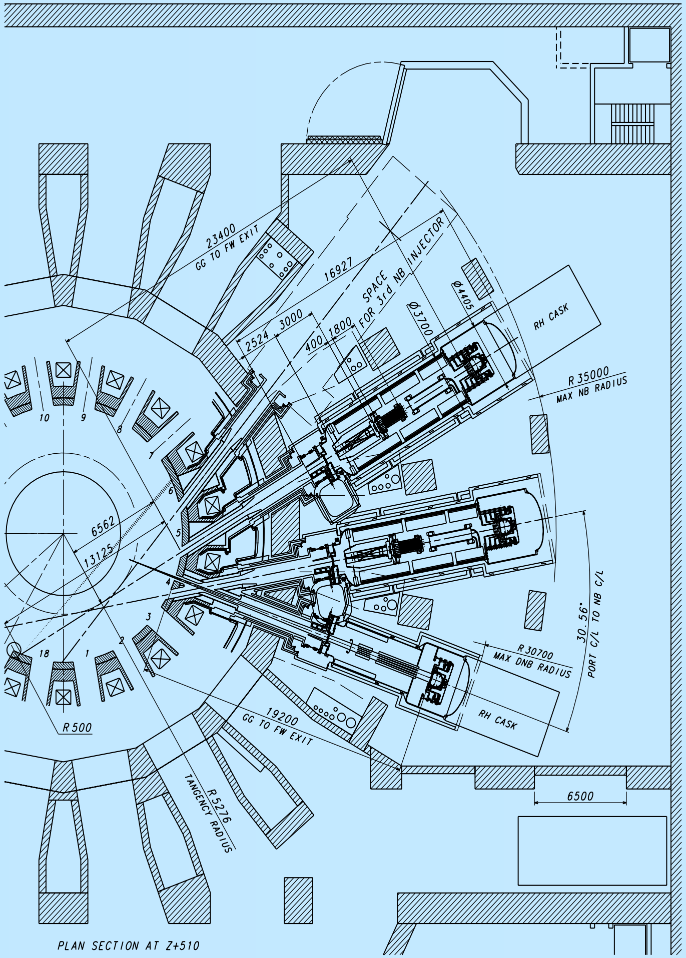
- **A reinforced single-shell cylinder 24m high and 28 m diameter.**
- **Attached to the vessel at the port extensions.**
- **Radiation heat in-leak from surrounding hot surfaces reduced by thermal shields close to magnets.**

Remote Maintenance of in vessel components is performed by cask based tools



Additional Heating





- **2 NBI beamlines (33MW), 1 ICRH antenna (20MW), 1 ECRH launcher (20 MW) and later either one LH launcher or additional ICRH or ECRH power are foreseen**

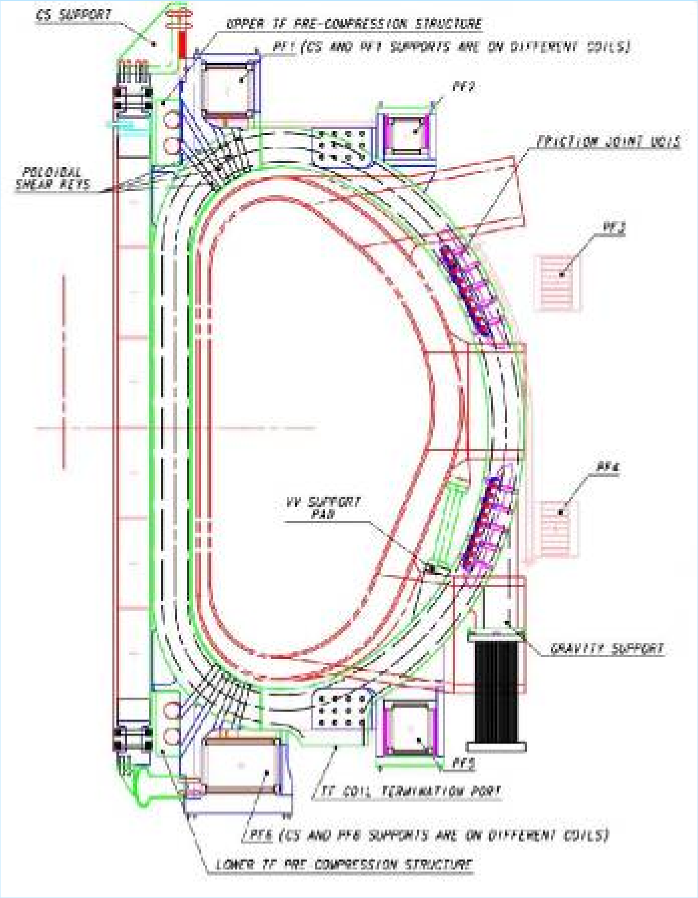
Underpinning R&D for ITER

- 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

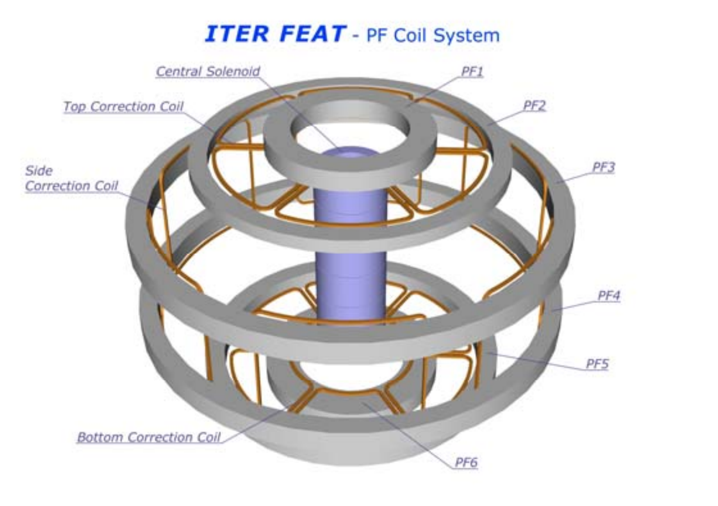
- Other R&D concerned safety-related issues, and auxiliary systems - heating and current drive, fuelling and pumping, tritium processing, power supplies and diagnostics, etc.

Design - Magnets and Structures (1)

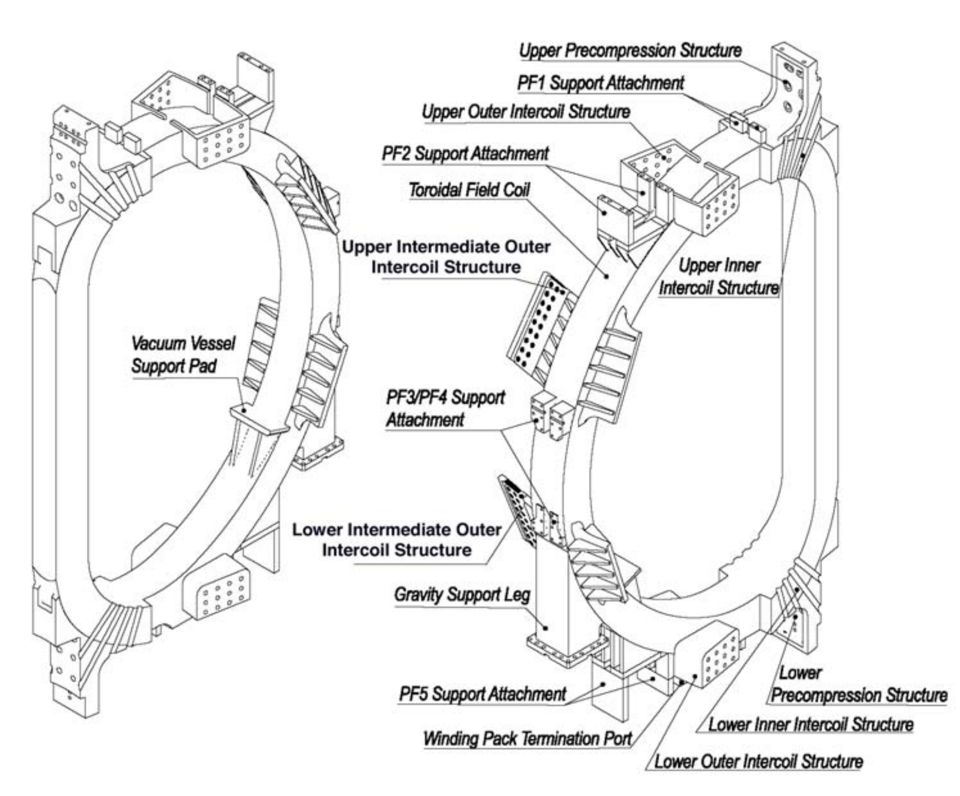


Superconducting. 4 main subsystems:

- **18 Nb_3Sn toroidal field (TF) coils produce confining/stabilizing toroidal field;**
- **6 NbTi poloidal field (PF) coils position and shape plasma;**
- **modular Nb_3Sn central solenoid (CS) coil induces current in the plasma.**
- **correction coils (CC) correct error fields due to manufacturing/assembly imperfections, and stabilize the plasma against resistive wall modes.**



Design - Magnets and Structures (2)

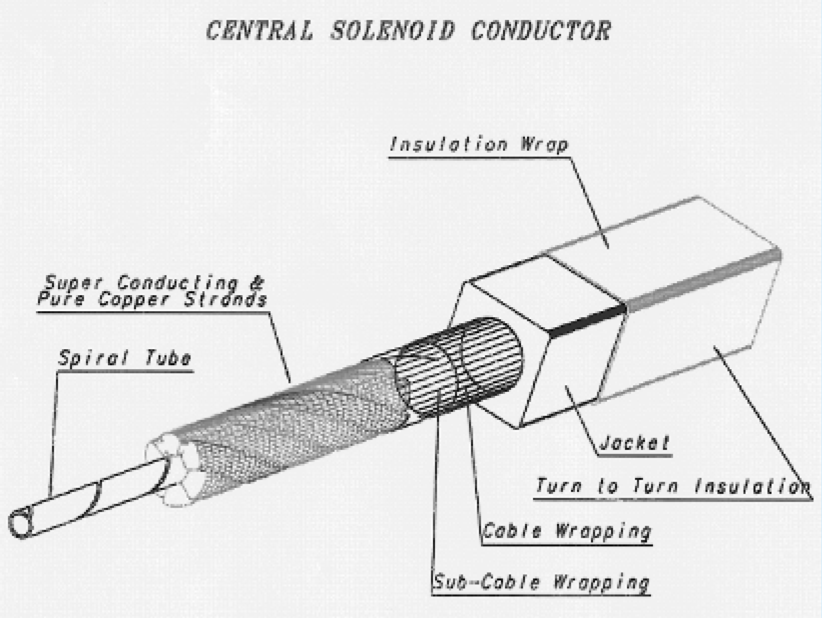


- **TF coil case provides main structure of the magnet system and the machine core. PF coils and vacuum vessel are linked to it. All interaction forces are resisted internally in the system.**
- **TF coil inboard legs are wedged together along their side walls and linked at top and bottom by two strong coaxial rings which provide toroidal compression and resist the local de-wedging of those legs under load.**
- **On the outboard leg, the out-of-plane support is provided by intercoil structures integrated with the TF coil cases.**
- **The magnet system weighs ~ 8,700 t.**

Design Feasibility - Magnets

- Cable-in-conduit conductors cooled with forced flow supercritical helium.
- TF, CS, PF conductors use circular cable with central cooling channel.

	TF	CS	PF	Correction
Current (kA)	68	42/46	45	10
Field (T)	11.8	13.5/12.8	6-4	<6
Superconductor	Nb_3Sn	Nb_3Sn	NbTi	NbTi
Jacket Type	circ, thin	square, thin	square, thick	square, thin
Jacket Material	steel	steel	steel	steel
Max single length (m)	760	812	807	364

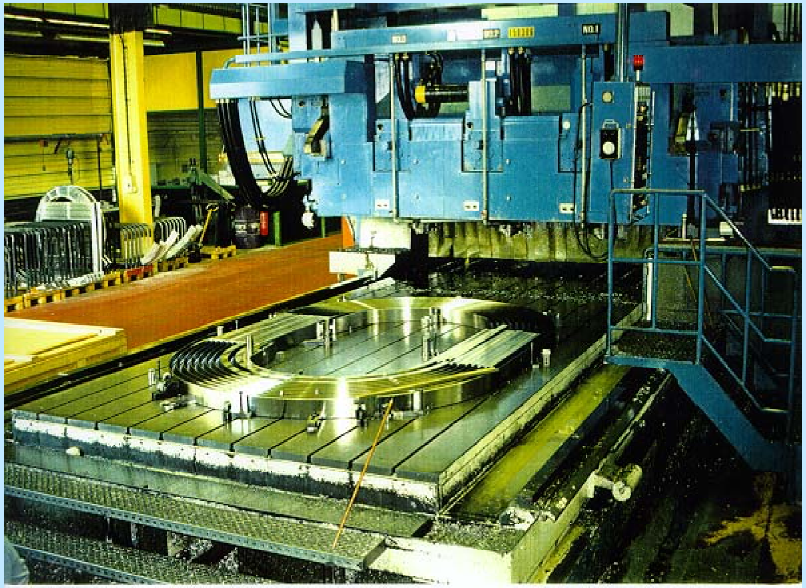


CS Model Coil

- **Largest, high field, pulsed superconducting magnet in the world. Similar in size and characteristics to one of the modules of the ITER CS.**
- **Uses ~ 25 t of strand. The inner module (US), the outer module (JA), and the insert coil (JA) were assembled at JAERI.**
- **Maximum field of 13 T with a cable current of 46 kA has been successfully achieved. Stored energy of 640 MJ at 13 T was safely dumped with a time constant as short as 6 s (vs. 11 s in the ITER CS).**
- **Picture shows the outer module being placed inside the inner module inside the vacuum chamber.**

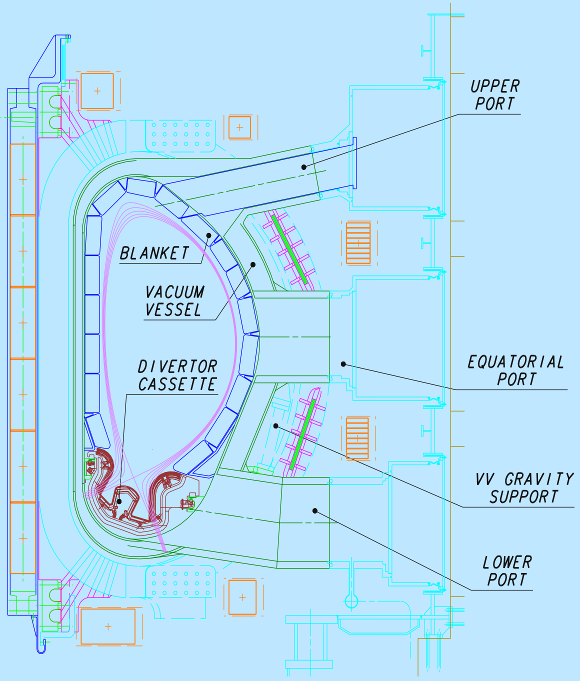
R&D - TF Model Coil (L-2) (2)

Conductor after heat treatment, opened out by ‘unspringing’ to give space to wrap with insulation without damaging the superconductor. The insulation has been applied to the lower turns. (Ansaldo Energia)



Machining of the radial plate which reinforces the conductor. The conductor is fitted into grooves in this plate. (Mecachrome/Nöll)

Design - Vessel, Blanket & Divertor (1)



The double-walled vacuum vessel is lined by modular removable components, including blanket modules composed of a separate first wall mounted on a shield block, divertor cassettes, and diagnostics sensors, as well as port plugs such as the limiter, heating antennae, and test blanket modules. All these removable components are mechanically attached to the VV.

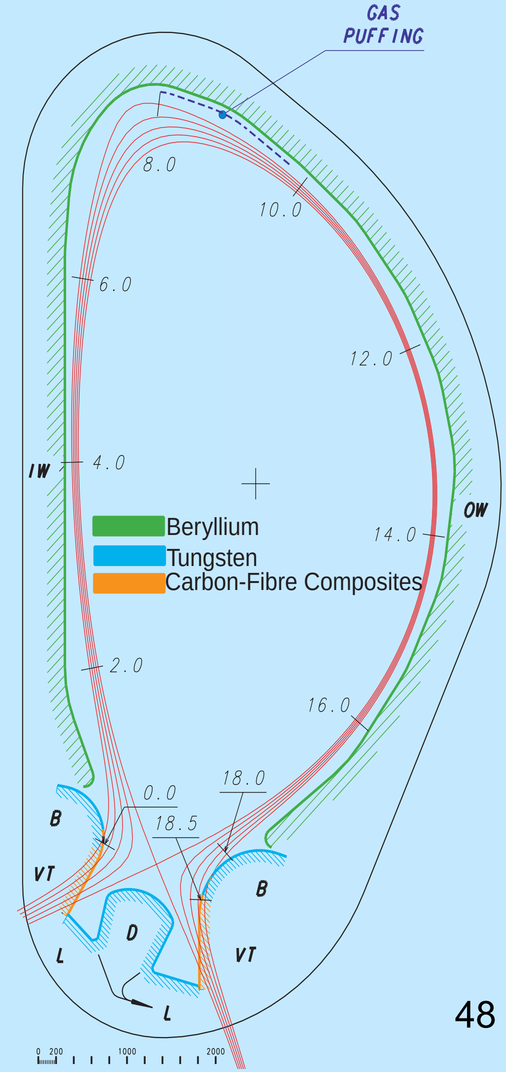
These vessel and internal components absorb most of the radiated heat from the plasma and protect the magnet coils from excessive nuclear radiation. This shielding is accomplished by a combination of steel and water, the latter providing the necessary removal of heat from absorbed neutrons. A tight fitting configuration of the VV to the plasma aids the passive plasma vertical stability, and ferromagnetic material in the VV located under the TF coils reduces the TF ripple and its associated particle losses.

Plasma Facing Materials issues

- **Issues for the CFC divertor targets are**
  - **Erosion lifetime (chemical sputtering), T-co-deposition (450g T limit inside the vessel) and C dust production (~200kg limit)**
- **Issues for the Be FW are**
  - **Be dust production (100kg limit) in particular on hot surfaces (6kg limit) -> Hydrogen production in off normal events - explosion?**
- **Issues for W clad divertor targets are**
  - **W dust production (100 - 300kg limit) causing a radiological hazard in case of a by-pass event**
  - **Disruption erosion - melt-layer loss**
  - **Plasma compatibility**

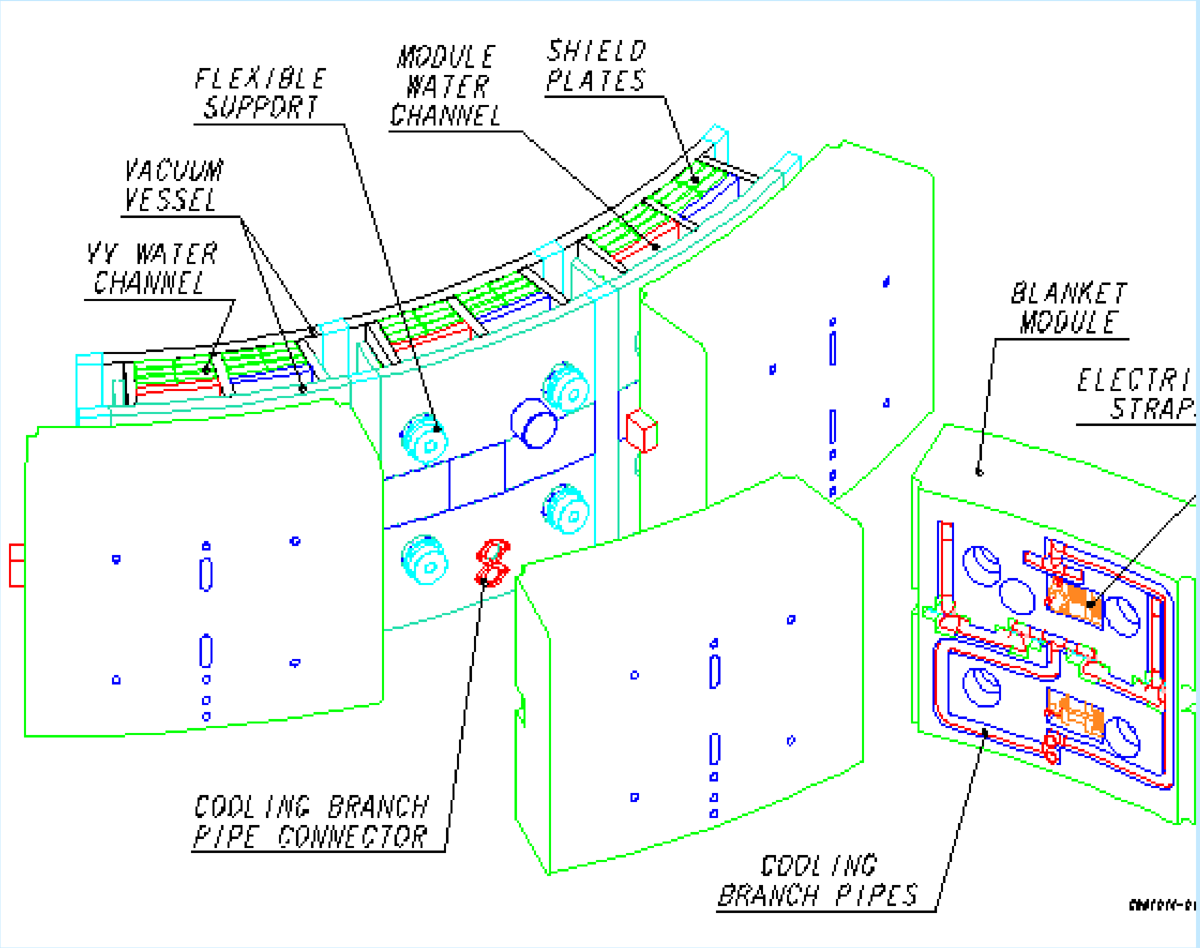
PFCs	**Area** (m^2)
IW	300
OW	380
L	10
B	50
D	30
VT	55
Liner	60

Present reference is to use three different PFMs (see picture)

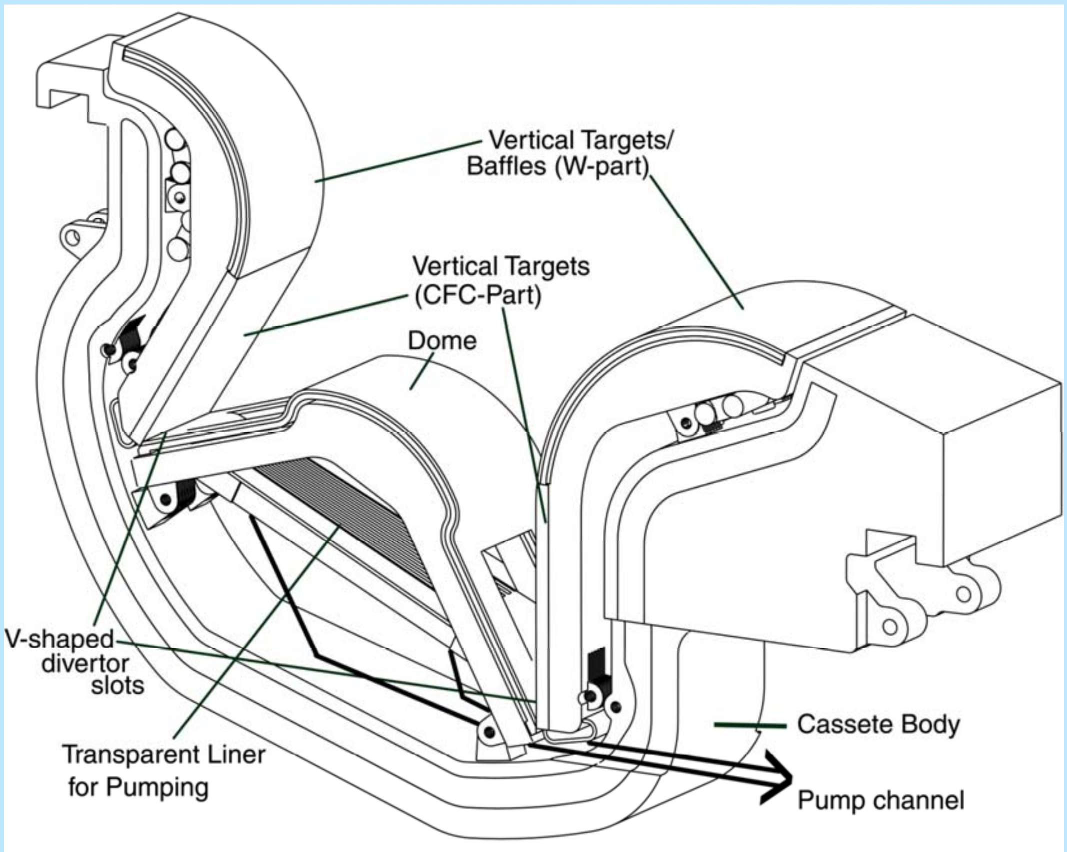


Blanket attachment scheme

Blanket attachment has to be flexible to allow bowing and thermal expansion but has also to withstand substantial electromagnetic forces (~ 150 tonnes torque and similar pushing and pulling forces)



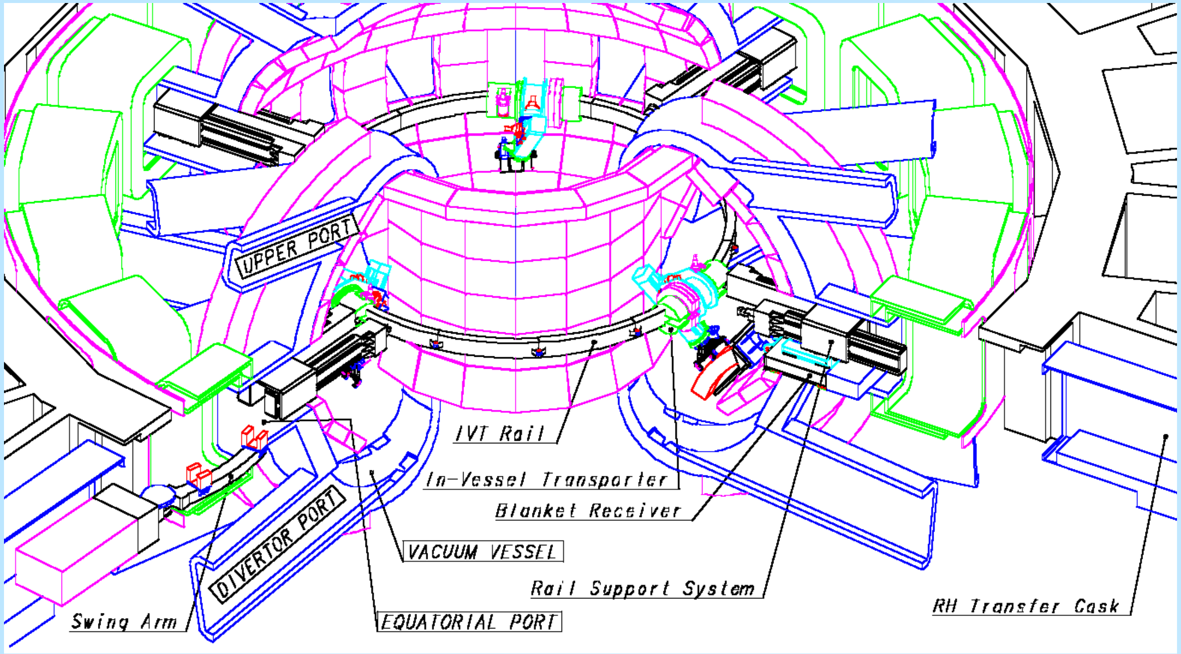
Design - Vessel, Blanket & Divertor (4)



The divertor is made up of 54 cassettes. The target and divertor floor form a V which traps neutral particles protecting the target plates, without adversely affecting helium removal. The large opening between the inner and outer divertor balances heat loads in the inboard and outboard channels.

The design uses C at the vertical target strike points. W is the backup, and both materials have their advantages and disadvantages. C is best able to withstand large power density pulses (ELMs, disruptions), but gives rise to tritiated dust and T codeposited with C which has to be periodically removed. The best judgement of the relative merits can be made at the time of procurement.

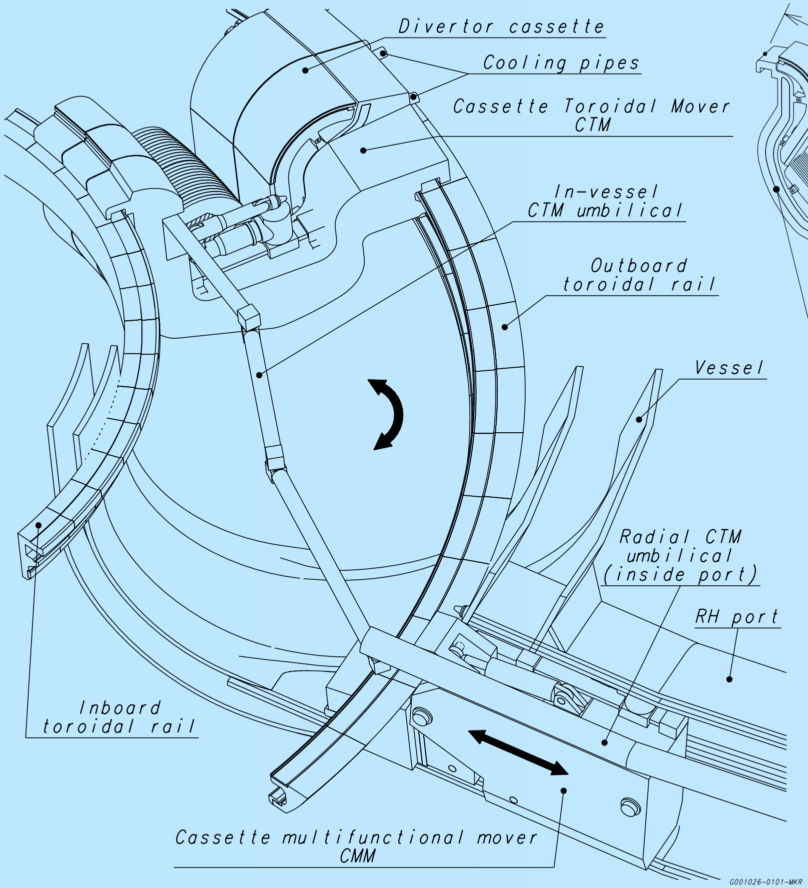
Design - In-vessel Remote Handling (1)

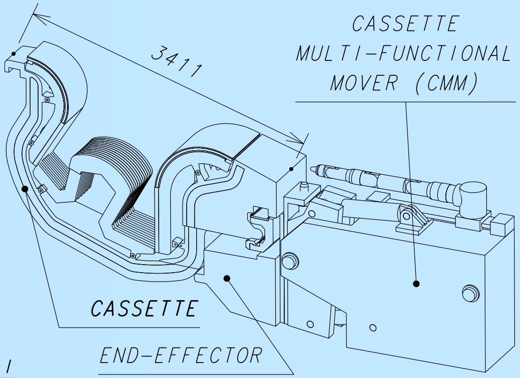


Systems near the plasma will become radioactive and will require remote maintenance, with special remote handling equipment. In-vessel transporters are used to remove and reinstall blanket modules.

Unshielded casks, which dock to the access ports of the vacuum vessel, house such equipment and transport radioactive items from the tokamak to the hot-cell where refurbishment or waste disposal can be carried out. Docking is tight, to avoid spread of contamination. Hands-on assisted maintenance is used wherever justifiable, following ALARA principles.

Design - In-vessel Remote Handling (2)



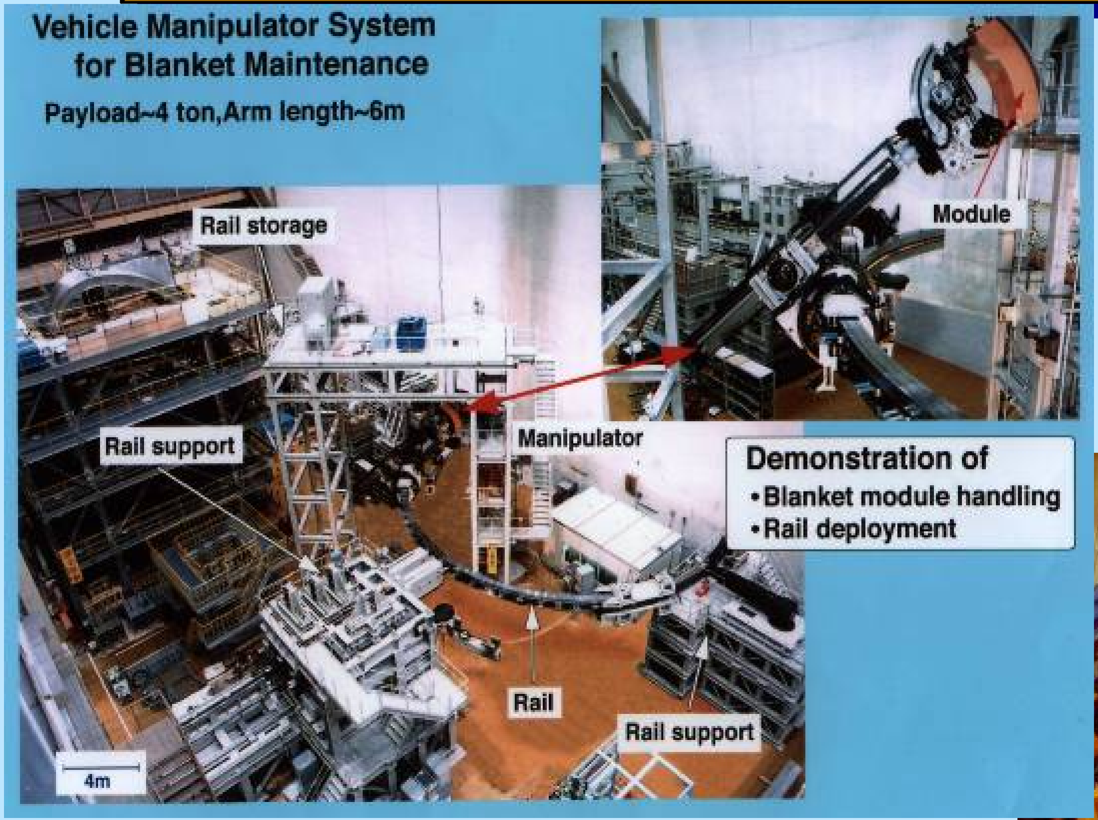


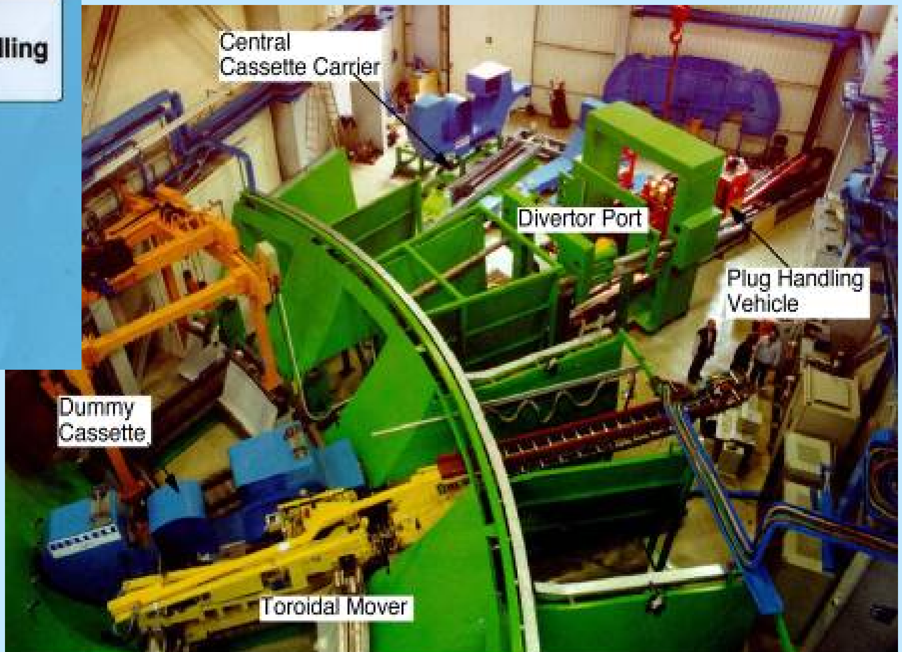
Multifunction manipulators are used for divertor cassette removal and to handle vacuum vessel port plugs. A toroidal mover slides the divertor cassettes along rails into their final position.

Comprehensive R&D has successfully demonstrated that key maintenance operations can be achieved using common remote handling technology.

Crucial issues such as vacuum vessel remote cutting and re-welding, viewing, materials and components radiation hardness have been addressed and demonstrated.

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.

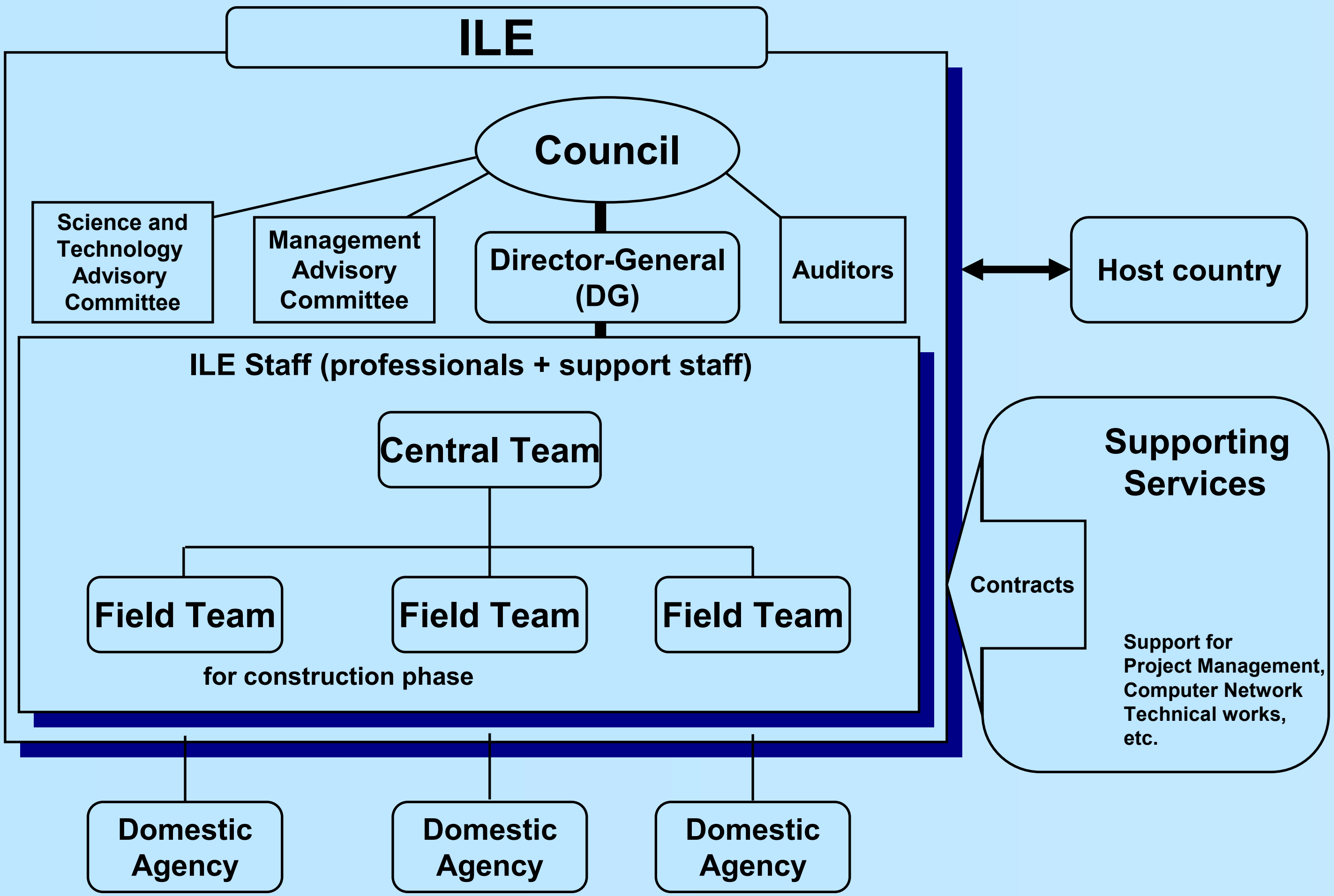
ITER Construction Valuation Method

- 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 $.

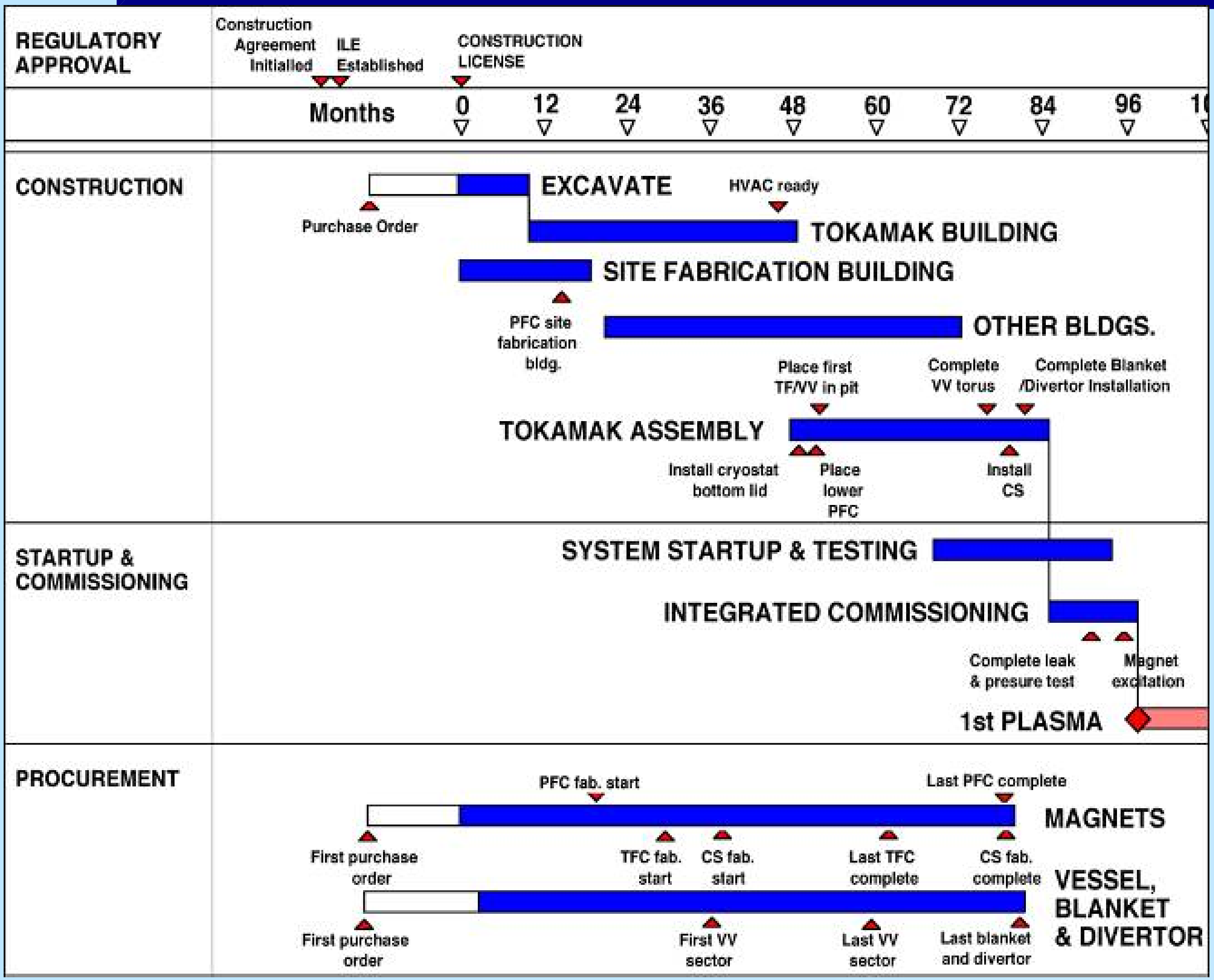
Indicative system costing

Components/Systems	**Indicative Cost (kIUA)**	**% of Total**
Magnet Systems Vac.Vessel, Blanket & Divertor Tokamak Power Supplies Diagnostics Other Main Tokamak Systems Heating Systems (73 MW total) Buildings, Site Facilities. & BOP	880 507 224 215 664 229 503	27 16 7 6 21 7 16
Total Direct Capital Costs	**3222**	**100**
Management and support	**480**	
R&D during construction	**≈70**	
Operation costs (average/year)		
- permanent personnel	**60**	
- energy + fuel	**≈30 + 8**	
- maintenance/improvements	**≈90**	
Decommissioning (without…)	**335**	

ITER Legal Entity



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 resolved (July 2005) in favour of the European site at Cadarache (France). The International Agreement should be signed soon (beginning of 2006?).

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