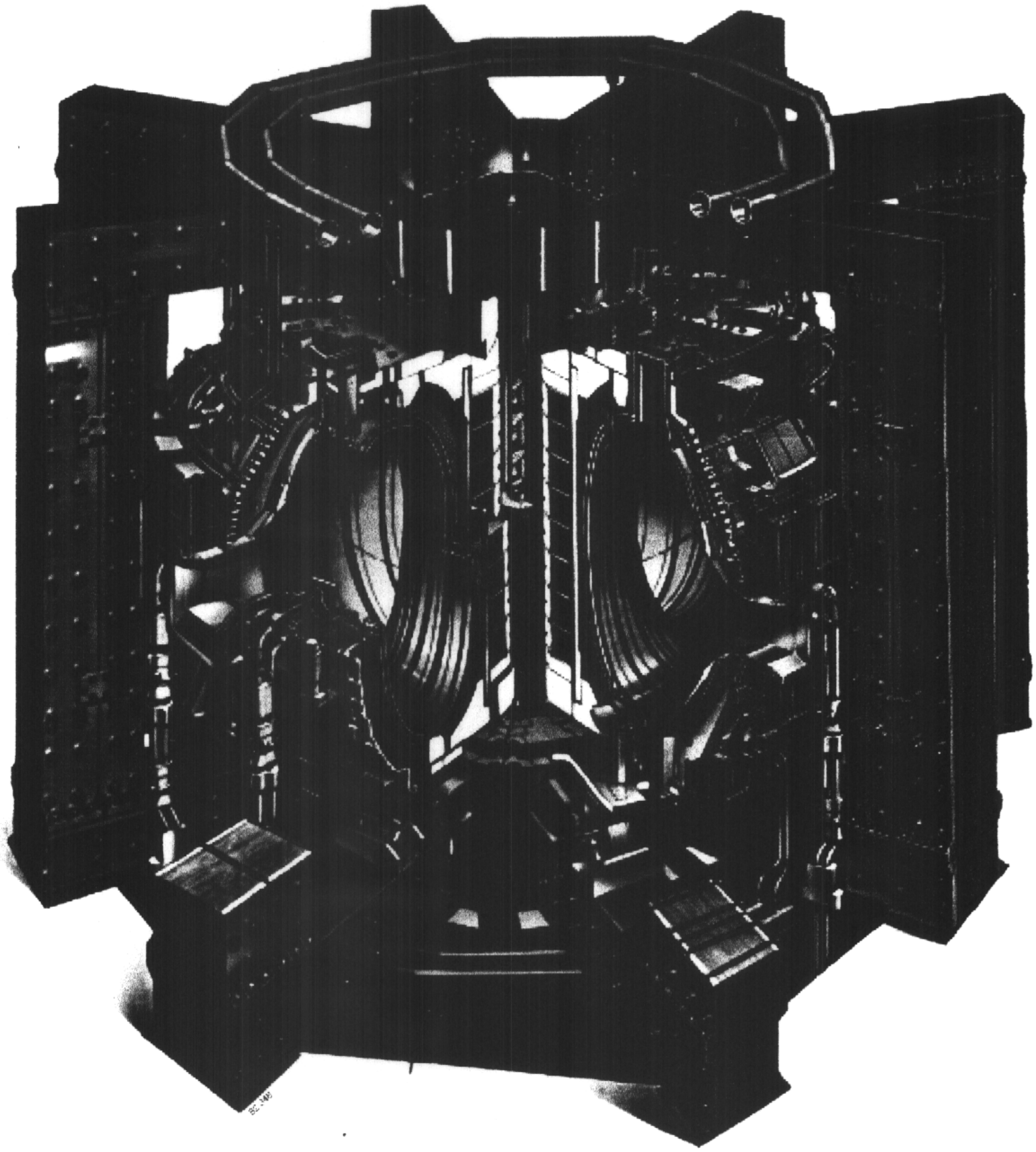
The JET Facilities
A Collaborative Experiment
(operating within EFDA)



A model for the Next Step

Presented by UKAEA on behalf of all the EFDA partners

EFDA

UKAEA

Fusion
Working with Europe

EFDA UROPEAN USION EVELOPMENT GREEMENT JET

JG00.203/1

JET

A MODEL FOR THE NEXT STEP

1. Fusion Energy

2. JET Design and Construction

3. Technical & Scientific Achievements

4. New Developments

5. ITER Prospects

6. Fusion and EEC Energy Strategy

7. Conclusions

Fuel Cycle in a Fusion Reactor

$$D + T \rightarrow {}^4He\ [\alpha] + N$$

[Reactor blanket containing Lithium]

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

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

$$D + Li = He + Energy$$

D in sea water (0.015% of H)

T produced in the reactor from Li

[Li abundant in earth crust]

Conditions for Fusion

In order to overcome the Coulomb repulsion forces the D-T mixture has to be heated at a temperature **T**>10 keV (plasma state)

For a sufficient reaction rate it is necessary to have a plasma at the required density **n**

These conditions have to be maintained for a time τ_E (energy confinement time), for the fusion reactions to be sustained by the energy of the α-particles produced by the D-T reactions

The fusion triple product must be:

$$\mathbf{n\tau_E T > 5x10^{21}\ [m^{-3} s keV]}$$

For magnetic confinement fusion

$\mathbf{n} \sim 2x10^{20}\ m^{-3}$, $\mathbf{T} \sim 2x10$ keV, $\tau_E \sim 1.5$

Breakeven and Ignition

$$D + T \rightarrow {}^4He + n$$

[3.5 MeV] [14.1 MeV]

If

P_α = power produced by alpha particles [^4He]

P_n = power produced by neutrons

P_H = power required to maintain plasma temperature and density

Then

Breakeven : $P_\alpha + P_n = P_H$

Ignition : $P_\alpha = P_H$

2. JET Design and Construction

3. Technical & Scientific Achievements

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OBJECTIVES OF JET

1972-73: *Joint European Working Group* defines objectives, outline design and main parameters of JET

1973 (September): *The JET Design Team* starts work at Culham

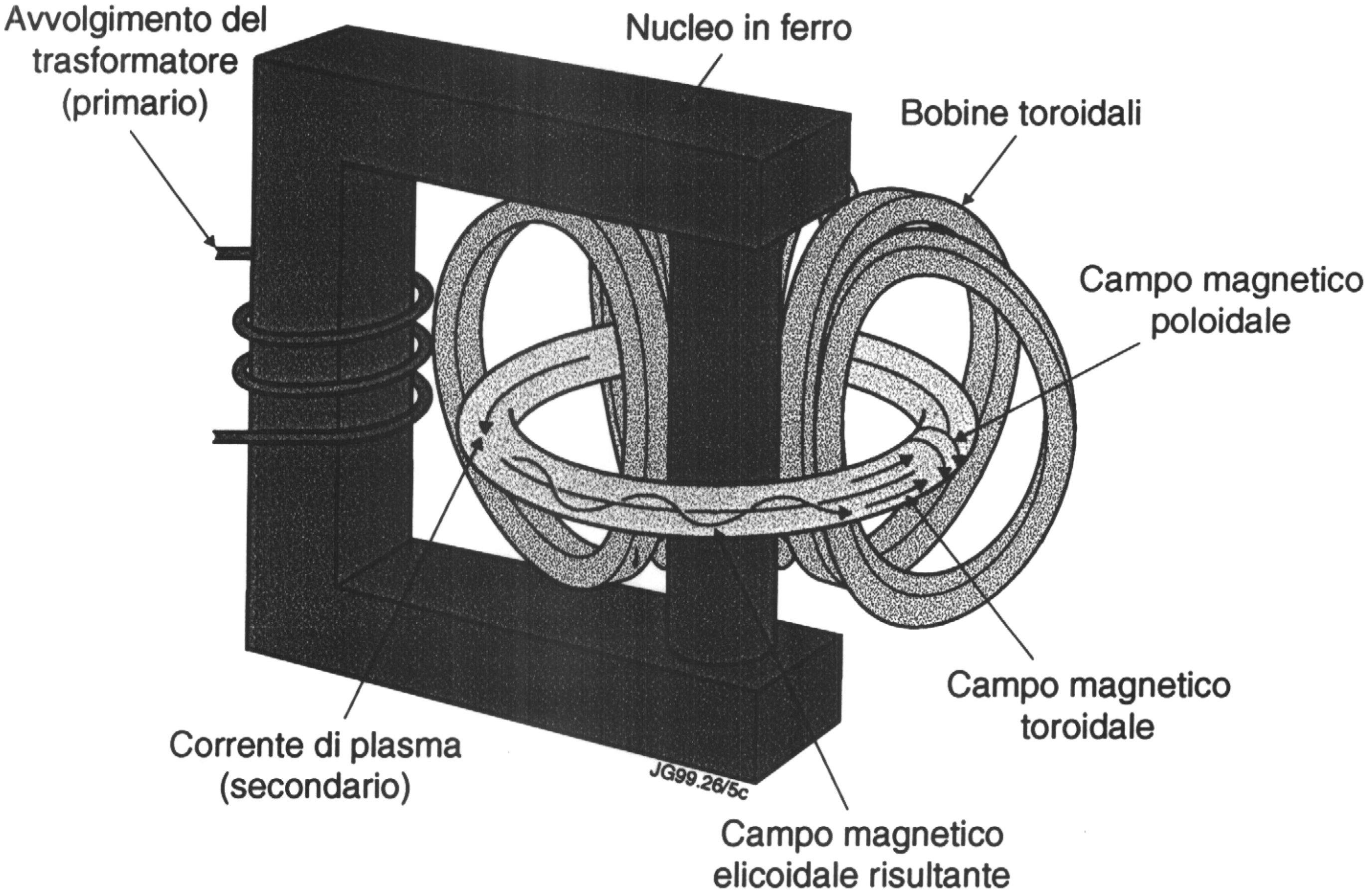
The essential objective of JET was to *study a plasma in conditions close to a fusion reactor*, including operation in *D-T*, i.e. to study:

- ***Scaling of plasma behaviour*** as parameters approach the reactor range
- ***Plasma-wall interaction*** and control of impurities with thermonuclear grade plasma
- ***Methods of plasma heating***, suitable to bring the plasma in the reactor regime
- ***Alpha particle production***, confinement and consequent plasma heating ***(D-T operation)***

Confinamento magnetico

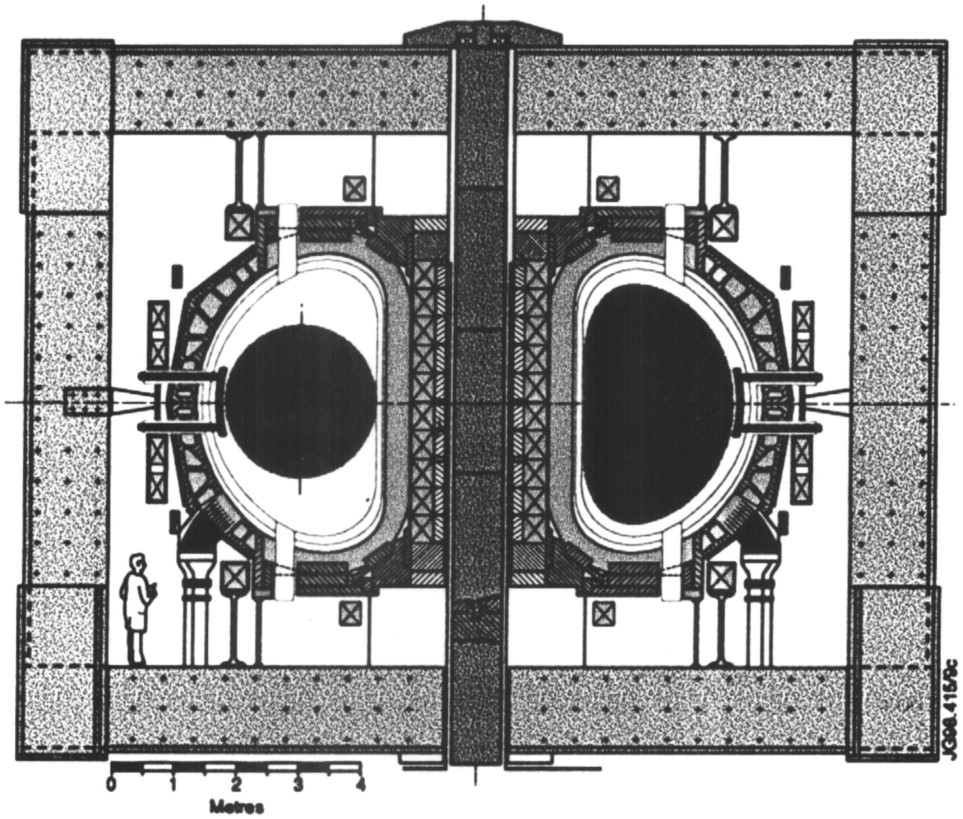
- Le *particelle del plasma* poiche' sono cariche (elettroni negativi e nuclei positivi) possono venire intrappolate da ***campi magnetici***, quindi confinate favorendo le collisioni tra i nuclei

- Si crea cosi' una '***bottiglia magnetica***', la piu' efficiente delle quali e' la configuarazione magnetica ***TOKAMAK***



DESIGN PHILOSOPHY (1)

- *Moderate toroidal magnetic field (3.4T)*, and *D-shape coils* to reduce electromechanical stresses, making a coil casing unnecessary, which also allows maximum access
- *Large number of toroidal coils (32),* to reduce magnetic field ripple
- *Large plasma volume (>100m^{-3})* and *current (design value 4.8MA D-shaped, 3MA, circular)*, *long pulse* capability *(20-60s)*, *D-shape vacuum vessel and plasma*, for the full use of the magnetic field volume
- *Double wall vacuum vessel*, to allow for first wall operation at high temperature *(350°C)* by interspace flow of hot air/ helium, and to act as double containement for tritium



Cross-section of the JET design

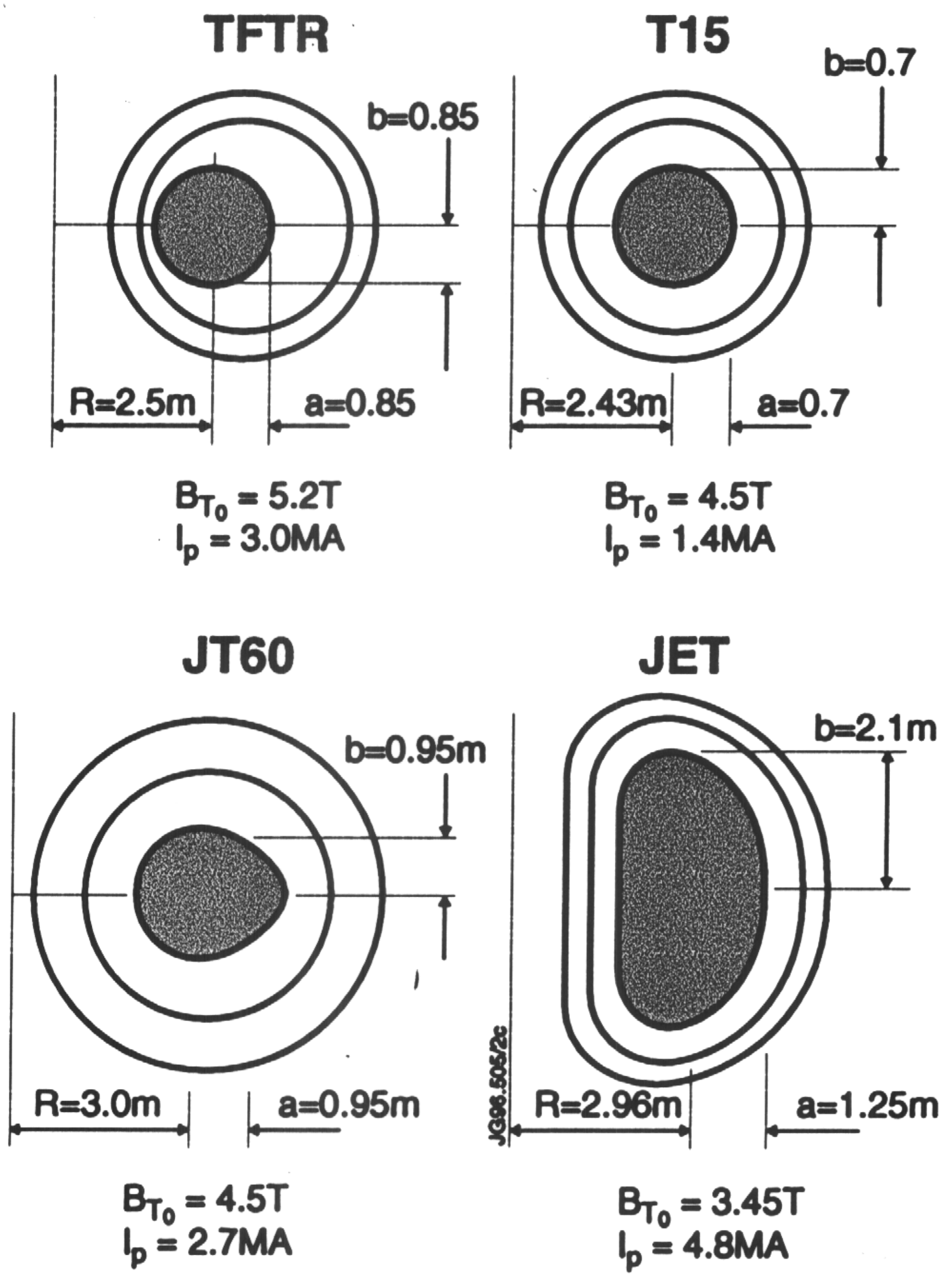
Main design parameters of JET

Parameter		Unit	Value
Major radius	R	m	2.96
Minor radius	a	m	1.25
Elongation	b/a	–	1.68
Magnetic field	B_T	T	3.45
Plasma current	I_P	MA	4.80
Operating time (at 3MA)	t	s	20
Plasma volume	V_P	m^3	150

JG92.36/11

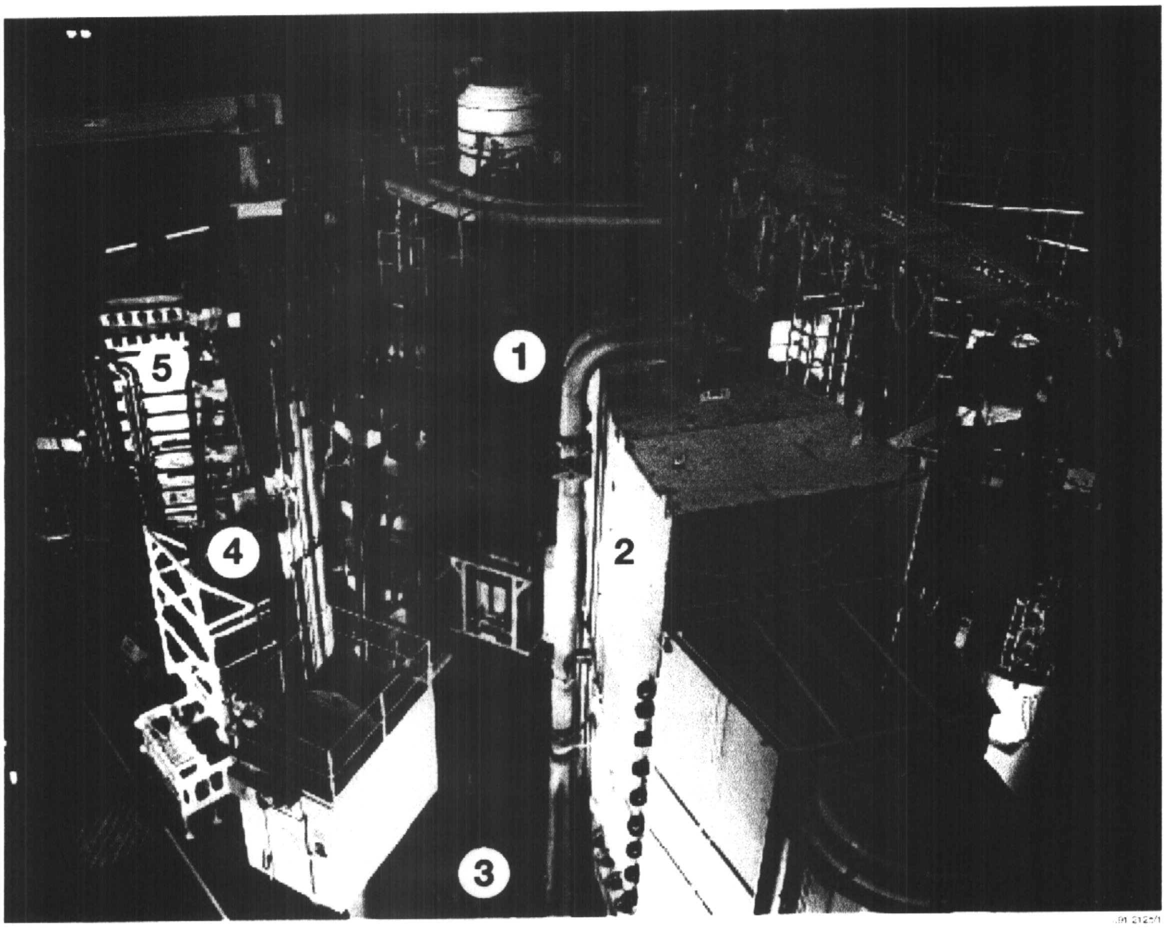
DESIGN PHILOSOPHY (5)

- Similar initiatives were taken by the *United States* with the *Tokamak Fusion Test Reactor* (TFTR), by *Japan* with the *Japanese Tokamak-60* (JT-60) and by the *Soviet Union* with the *Tokamak-15* (T-15)



Schematic cross-sections of the four *Large Tokamaks*

Overall view of the JET Machine



1 The Tokamak

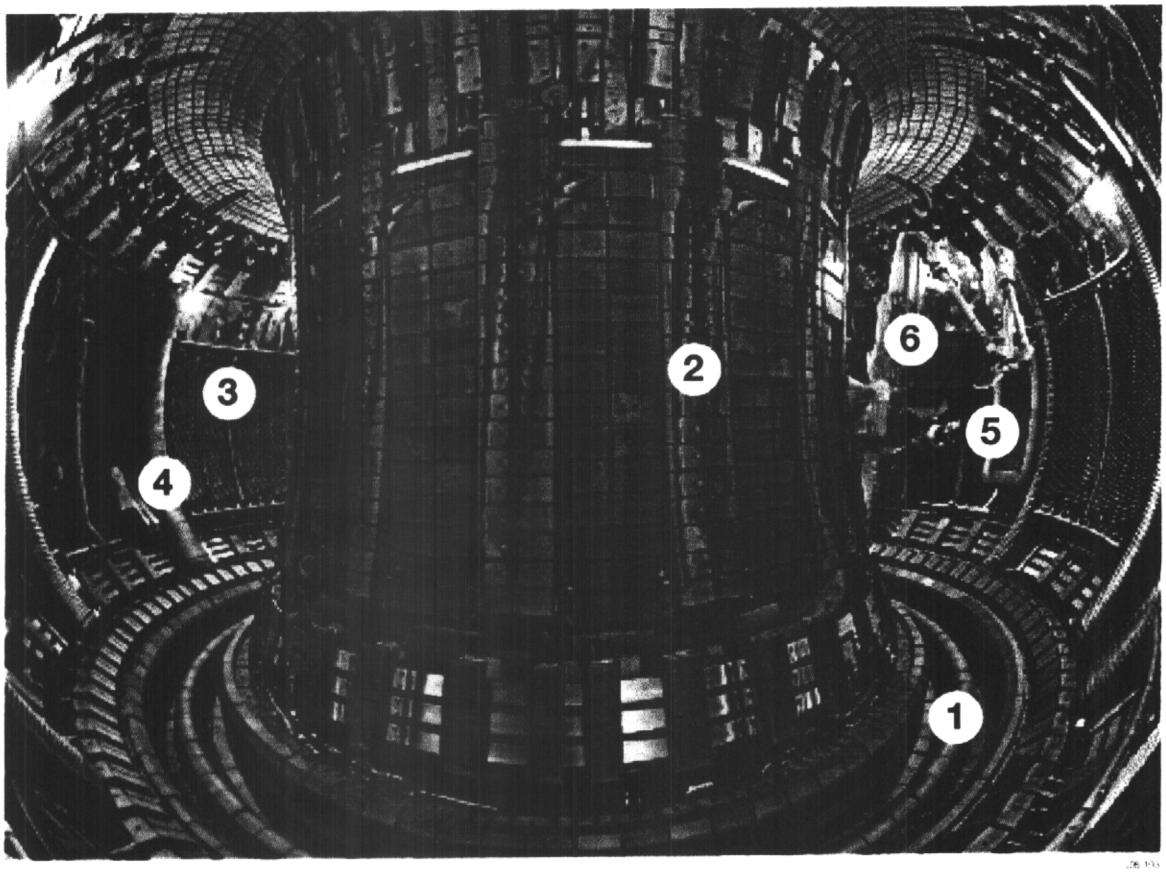
2 Neutral Beam Box (Octant 8)

3 ICRH Transmission lines

4 LH Launcher

5 Pellet Injector Box

Inside the JET Vacuum Vessel



1 Mark IIA Divertor

2 Inner Wall Limiters

3 RF Antennae

4 Outer Limiter

5 LH Launcher

6 MASCOT Servomanipulator (in vessel maintenance)

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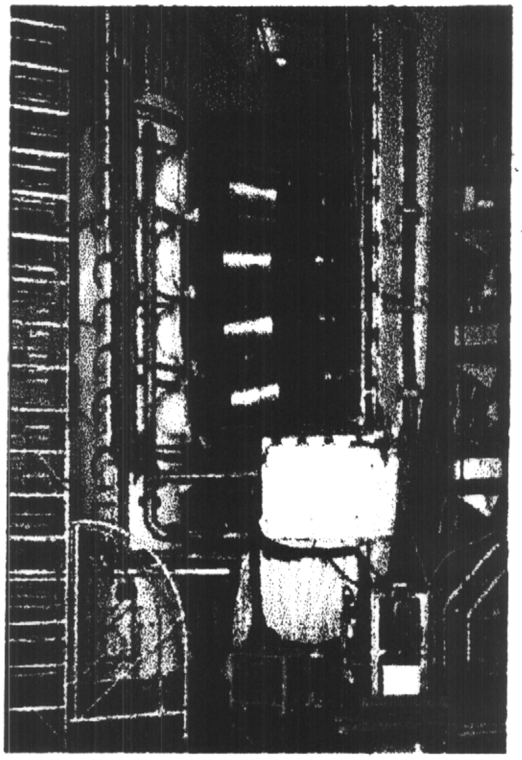
CONSTRUCTION (2)

Plasma heating and current drive systems

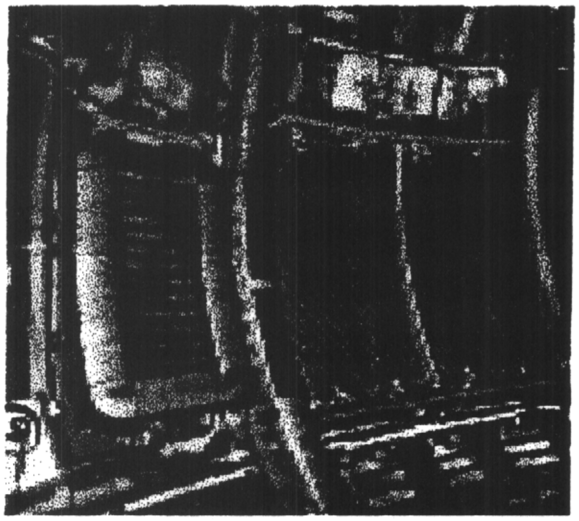


- There are *16 Neutral Beam Injection lines arranged in two units of 8*. Each line is capable to operate at *80kV, 60A* or at *160kV, 30A*, with a total heating power of *20MW*

  The two units or *"boxes"*, of 8 lines each, inject power through "Octant 4" and "Octant 8"

- *Four pairs of Ion Cyclotron Frequency (ICRF)* antennae are installed on the outer side of the vacuum vessel first wall, operating at *25-55MHz*, with a total heating power of *20MW*

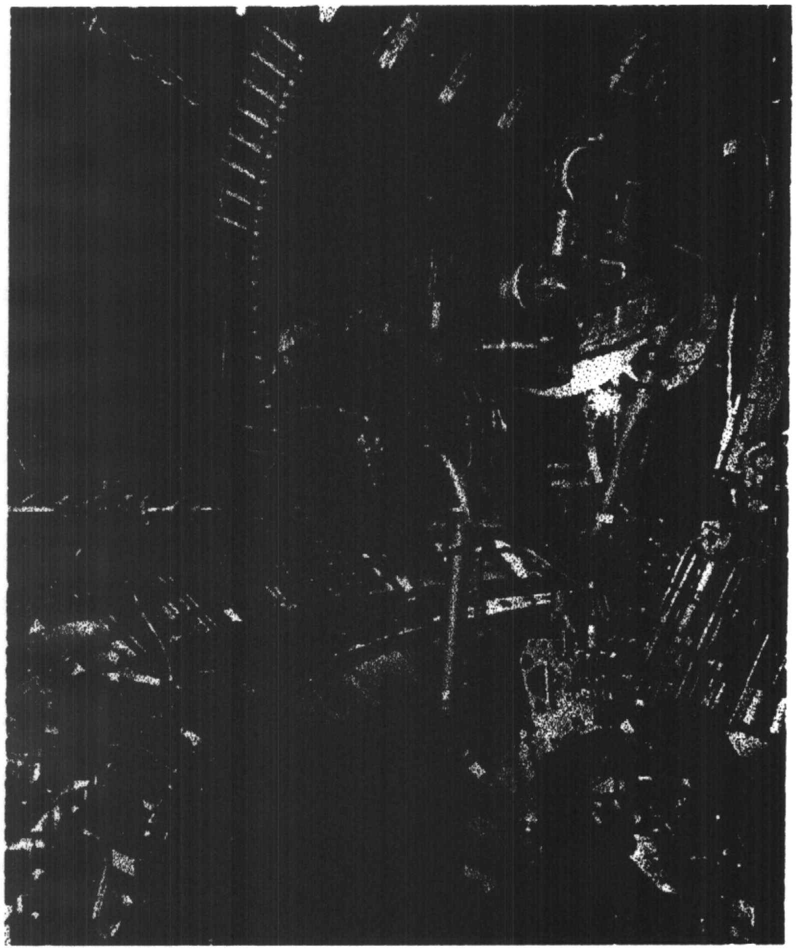
- One *Lower Hybrid Frequency (LHCD)* launcher, operating at *3.7GHz*, can supply up to *10MW* to the plasma and can control plasma current profiles and can drive the plasma current



D-T TECHNOLOGIES (2)

Remote Handling

- A wide range of ***transporters***, ***tools*** and ***procedures***, for in-vessel and ex-vessel intervention in active conditions, have been developed



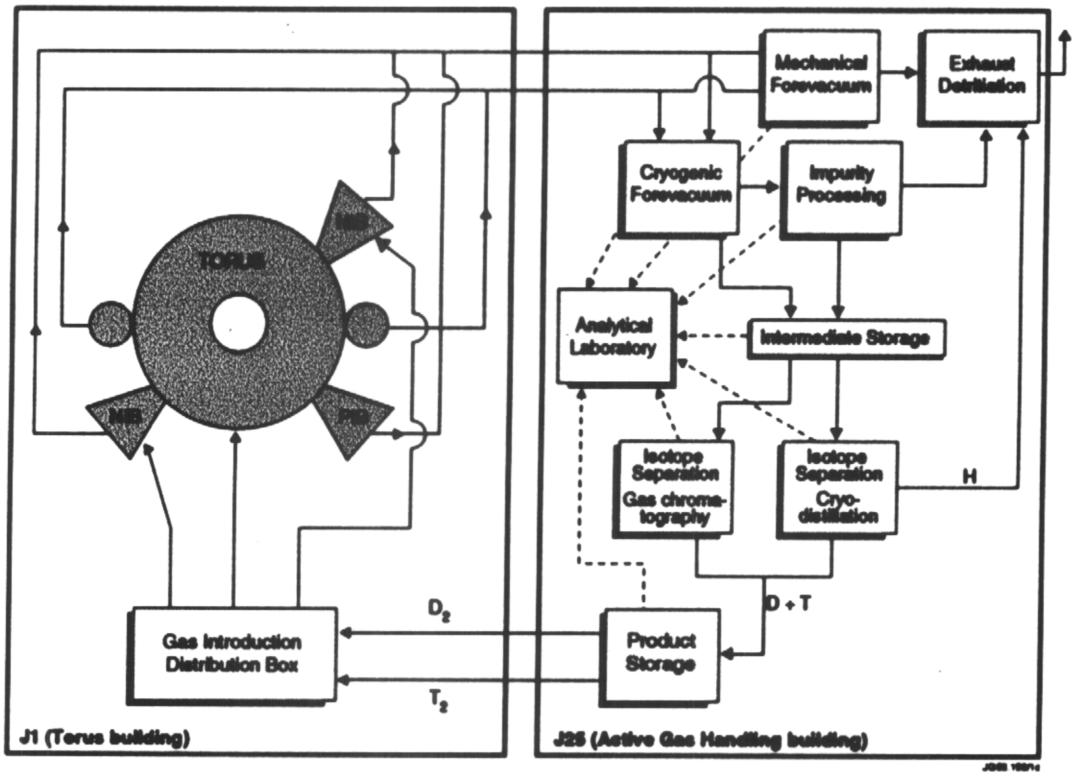
- The key RH tool is the Mascot IV Servomanipulator. It consists in a ***Master Unit*** and in a ***Slave Unit*** and it uses the ***man-in-the-loop*** technique, essential for unscheduled interventions. The Slave Unit, provided with ***TV cameras***, is transported and supported, while working in the vessel, by the main transporter, the ***Articulated Boom***

D-T TECHNOLOGIES (1)

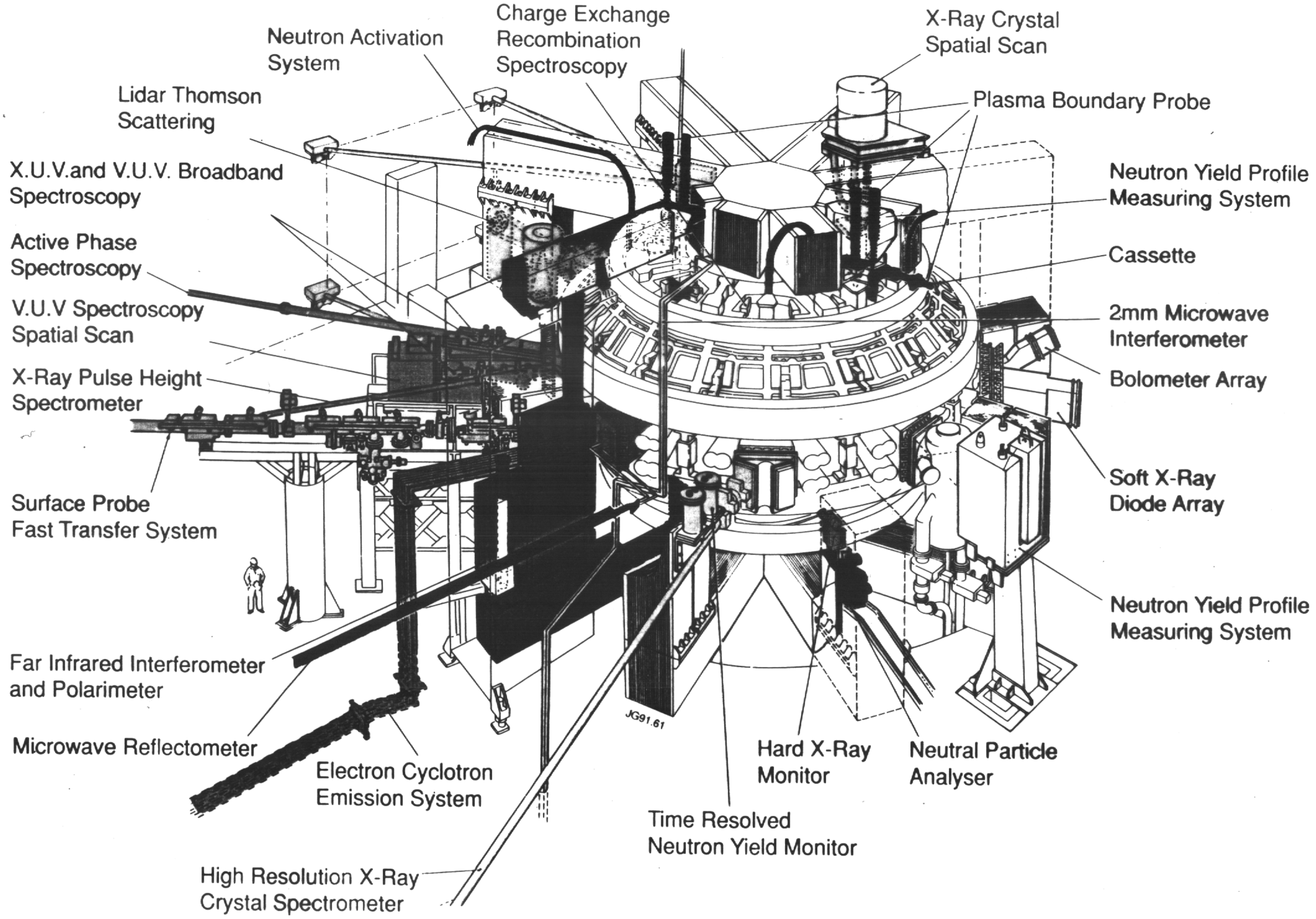
D-T technologies were developed in JET since the early design phase

- Principal D-T technologies are:
  - *– Active Gas Handling System (AGHS)*
  - *– Remote Handling Tools (RH)*

Active Gas Handling System



It *reprocesses* the exhaust fuel. It *pumps* the exhaust gas from the Torus and from the NB Injectors, it removes the ***impurities*** and separates the hydrogen gases into streams of ***protium***, ***deuterium*** and ***tritium***, it stores D and T in U-beds, for re-use in subsequent experiments. The isotope separation is obtained by ***gas-chromatography*** and by ***cryo-distillation***


Neutron Activation System
Charge Exchange Recombination Spectroscopy
X-Ray Crystal Spatial Scan
Lidar Thomson Scattering
Plasma Boundary Probe
X.U.V.and V.U.V. Broadband Spectroscopy
Neutron Yield Profile Measuring System
Active Phase Spectroscopy
Cassette
V.U.V Spectroscopy Spatial Scan
2mm Microwave Interferometer
X-Ray Pulse Height Spectrometer
Bolometer Array
Soft X-Ray Diode Array
Surface Probe Fast Transfer System
Neutron Yield Profile Measuring System
Far Infrared Interferometer and Polarimeter
Microwave Reflectometer
Electron Cyclotron Emission System
Hard X-Ray Monitor
Neutral Particle Analyser
Time Resolved Neutron Yield Monitor
High Resolution X-Ray Crystal Spectrometer
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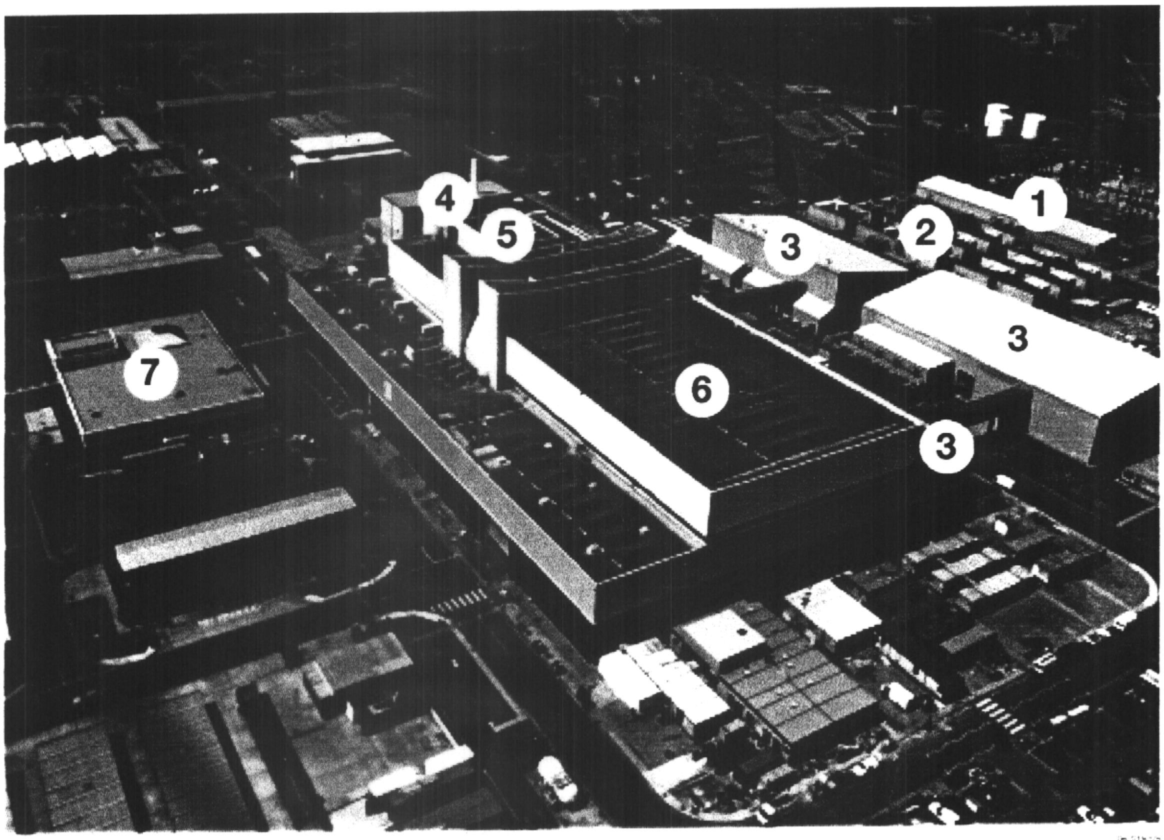
The JET Building at the Culham Site



1 400kV/33kV Substation

2 Outdoor Power Supplies (NBI, ICRF, LHCD)

3 Indoor Power Supplies (TF, PF, Divertor Coils)

4 Tritium Building

5 JET Tokamak Hall

6 Assembly Hall

7 Control Room

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3. Technical & Scientific Achievements

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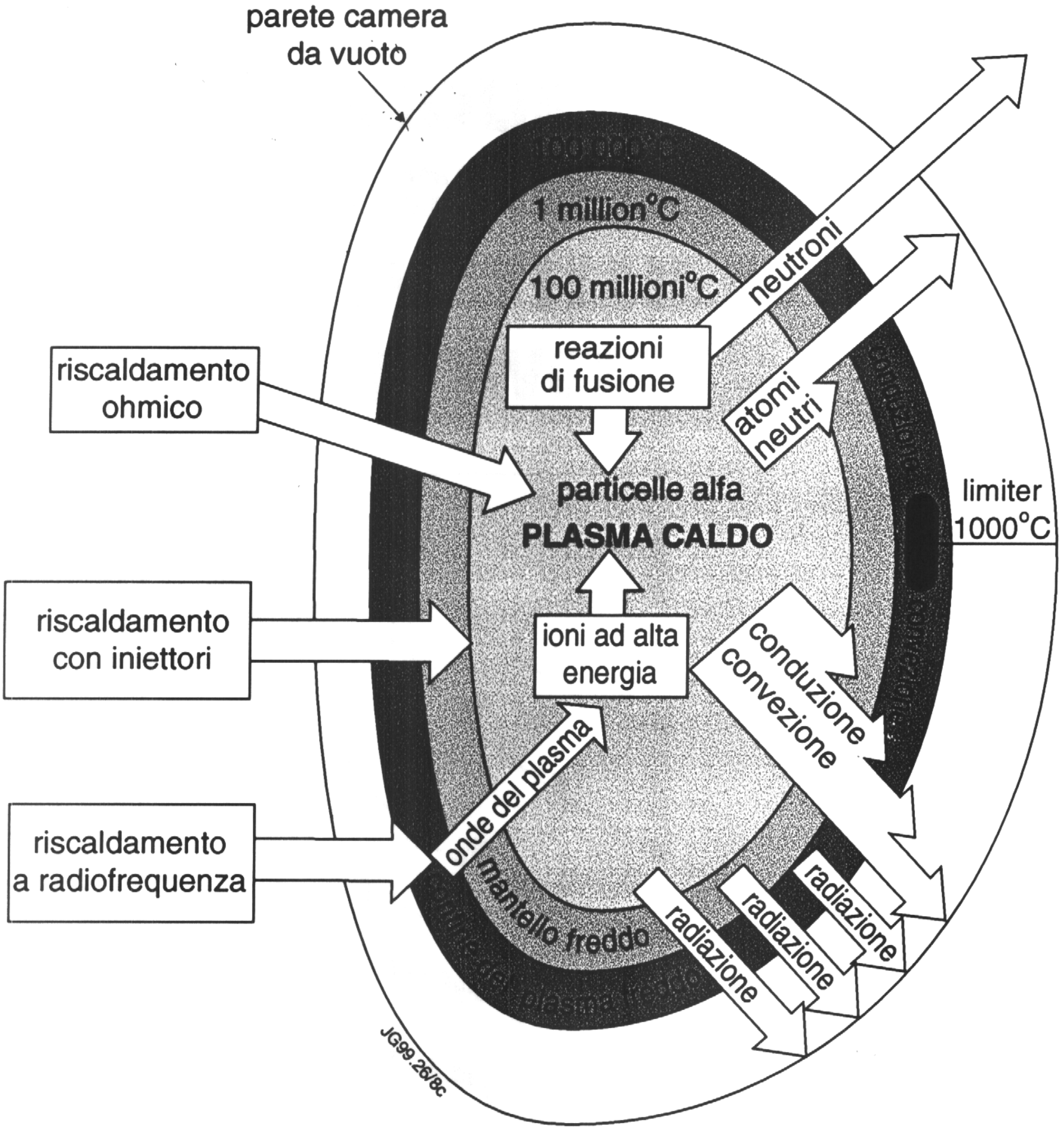
Bilancio energetico del plasma in un tokamak



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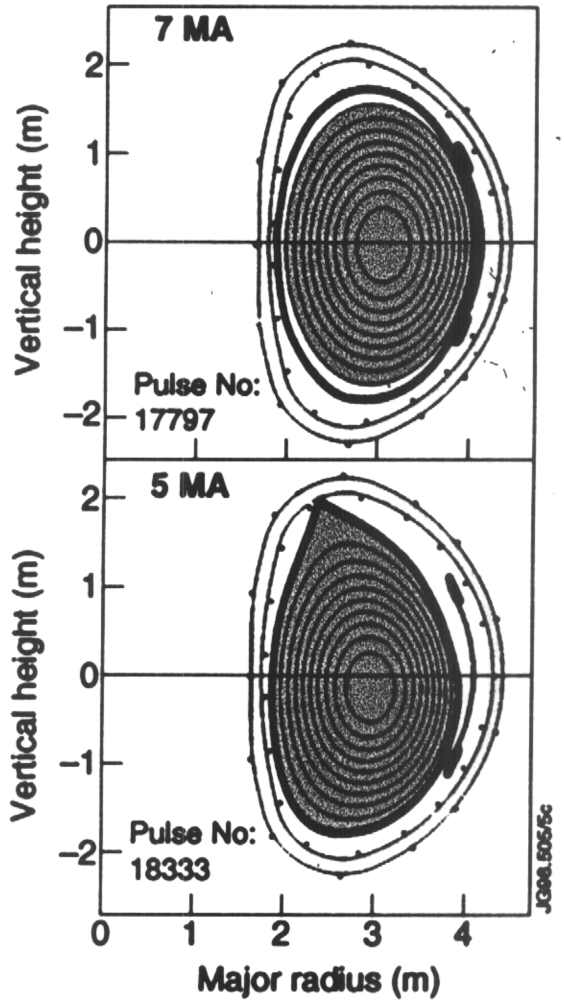
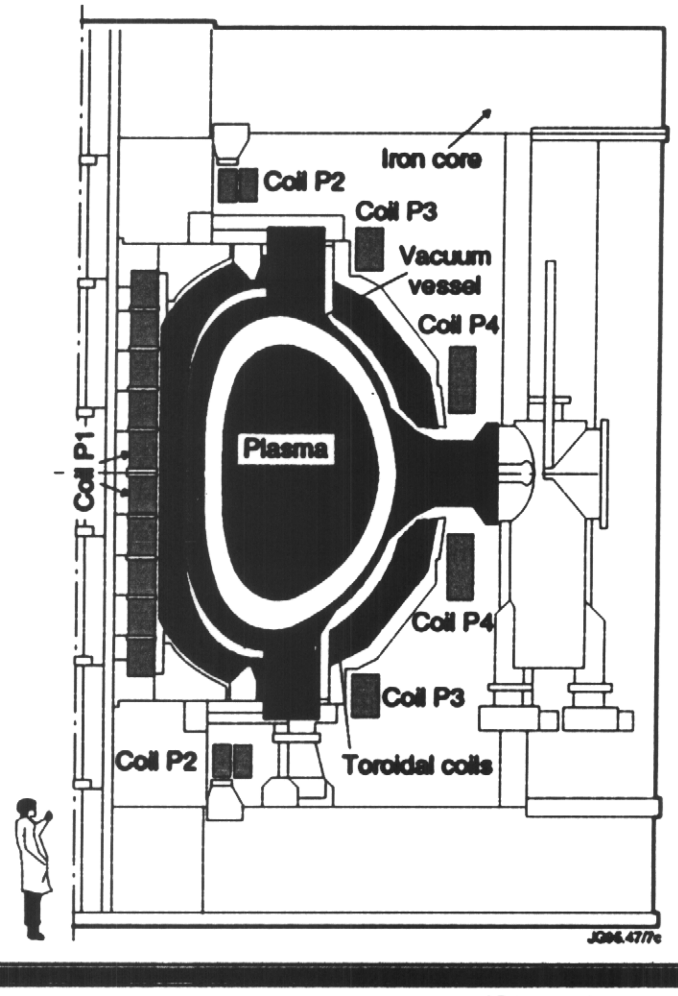
MAJOR MACHINE UPGRADING (1)



- The ***electro-magnetic system of the machine*** was modified to allow larger plasma currents, ***7MA with limiter***, and **5MA with X-point**, by increasing from 40 to 60MA the maximum current in the six (out of 10) inner pancakes of the central solenoid, taking advantage of the pre-compression exercised by the toroidal coils

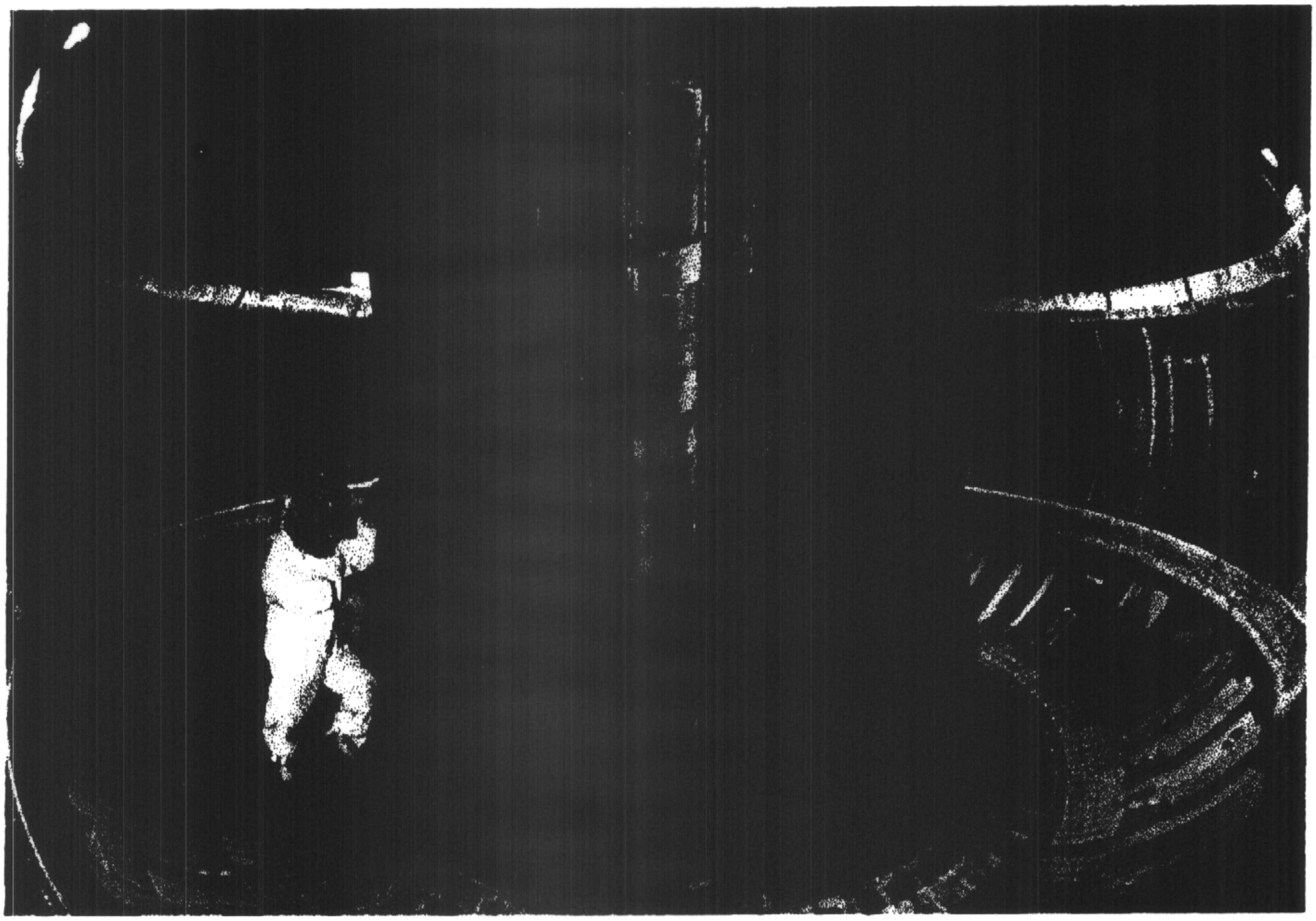
- To this aim only ***new power supplies*** to feed the 6 central pancakes of the central solenoid were to be purchased.

- Infact the re-assessment of the electromechanical system of the machine, indicated that the associated ***higher stresses*** were still within the ***machine capability***.



MAJOR MACHINE UPGRADING (2)

- Since early JET operation, it was clear that impurities were hampering progress in plasma performance, since Z>1 atoms enhance ***radiation losses*** ***($n_e > n_i$)*** and ***dilute the fuel*** ***($n_i > n_{DT}$)***
- In order to ***reduce the impurity parameter Z_{eff}***, the inconel first wall was progressively covered with ***graphite tiles***, as done in the smaller tokamak TEXTOR (G), and later also by ***beryllium tiles*** in critical areas, with the addition of off-pulse ***beryllium evaporation*** onto the vessel walls



Vacuum vessel walls covered with C and Be tiles

GLOBAL PERFORMANCE WITH MARK I

- To make room for the divertor inside the vessel, the space available to the plasma is reduced, which adversely effects performance
- The plasma discharges have been optimised with divertor to such an extent that, in spite of the reduction of the ***plasma volume to 80%***, global plasma performance were maintained: $n_D \tau_E T_D \sim 1.0 \times 10^{21}$ [m^{-3}skeV] and $Q_{DT} \sim 1$

Experimental Programme	Peak Ion* densities n_i (10^{20} m^{-3})	Peak Ion* temperature T_i (keV)	Energy* confinement time τ_E (s)	Z_{eff}	Fusion product $n_i \tau_E T_i$ (10^{20} m^{-3}s keV)	Equivalent Q_{DT}
Ohmic Heating (1983–1984)	0.4	3.0	1.0	3–10	1.2	0.01
Additional heating (1984-1986)	0.5	12.0	0.9	2–5	2.0	0.3
Machine upgrading (1986–1991)	1.2	20.0	1.2	2–3	2.5	0.3
Passive Control of Impurities (1988–1991)	4.0	30.0	1.8	1–2	9	1.07
Mark I Divertor (1994–1995)	1.0	28.0	1.0	1–2	10	1.0

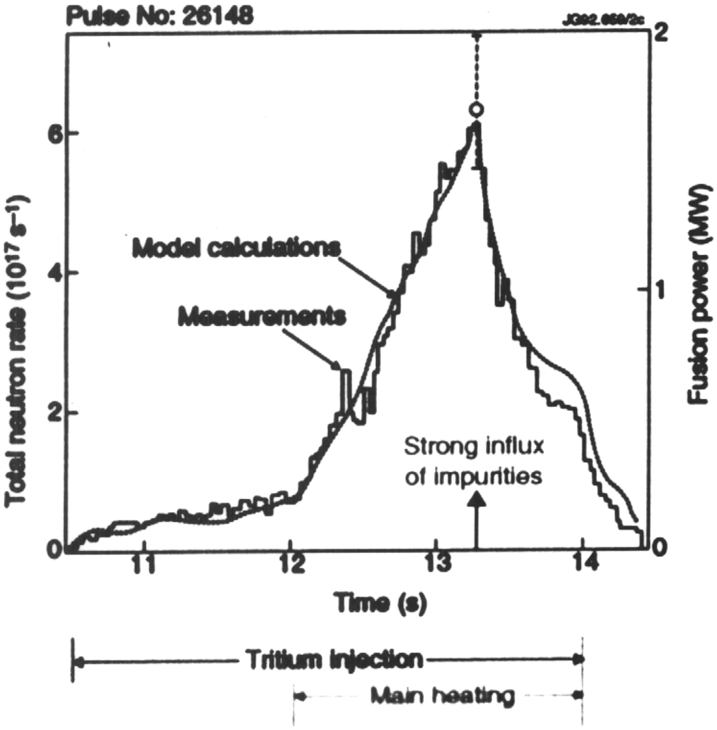
JG98.505/8c

PRELIMINARY TRITIUM EXPERIMENT (PTE)

These good *plasma performance*, suggested the ***use of tritium*** for the *first time* in a laboratory fusion experiment. Two pulses were allowed, to limit neutron production below the total production through the years in D-D experiments ($\sim 5 \times 10^{18}$).

9th NOVEMBER 1991

- 10% Tritium - 90% deuterium
- 14.3 MW of NB heating
- 1.7MW peak fusion power
- 2MJ of fusion energy
- Neutron/pulse ~ 0.6×10^{18}
- >50% of thermal neutrons
- Successful demonstration of tritium handling



- ***This result had an unprecedented impact on the media leading to a broad public perception of the potential of fusion energy***

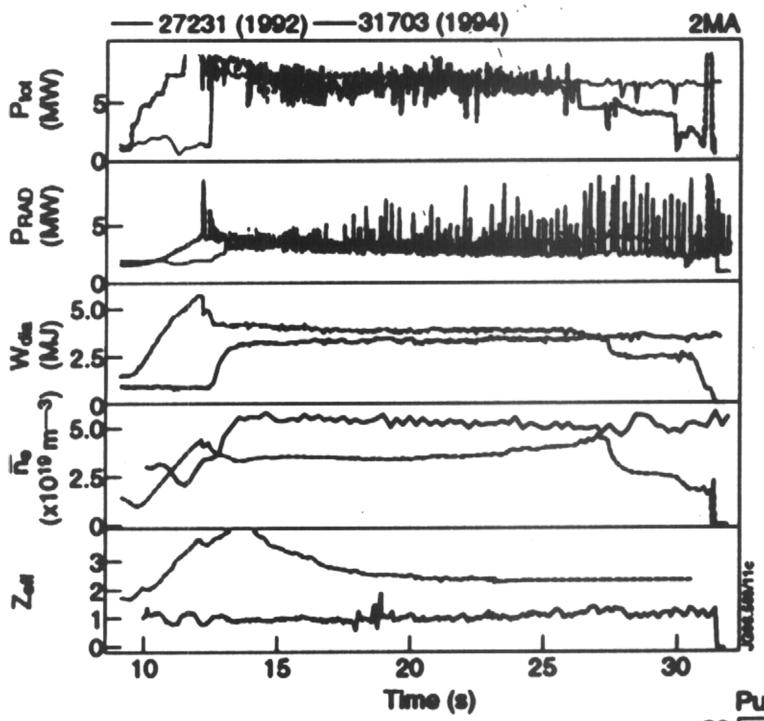
- ***Subsequently in 1994 the US experiment TFTR achieved fusion power in excess of 10MW***

JET

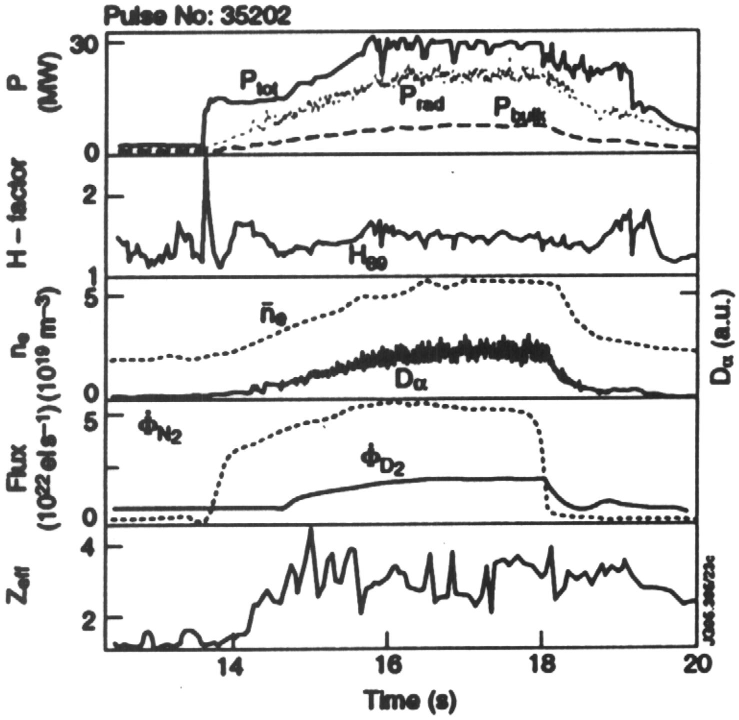
RESULTS WITH MARK I

The *divertor is effective*, i.e. the influx of impurities in the plasma can be controlled:

- In H-mode configuration, ***without divertor only 15MJ*** led to a 'carbon bloom', while ***with divertor 180MJ*** or more could be injected without plasma deterioration



Plasma performance were maintained in steady state for 20s (40 τ_E), only limited by machine constraints, at Z_{eff} ~1



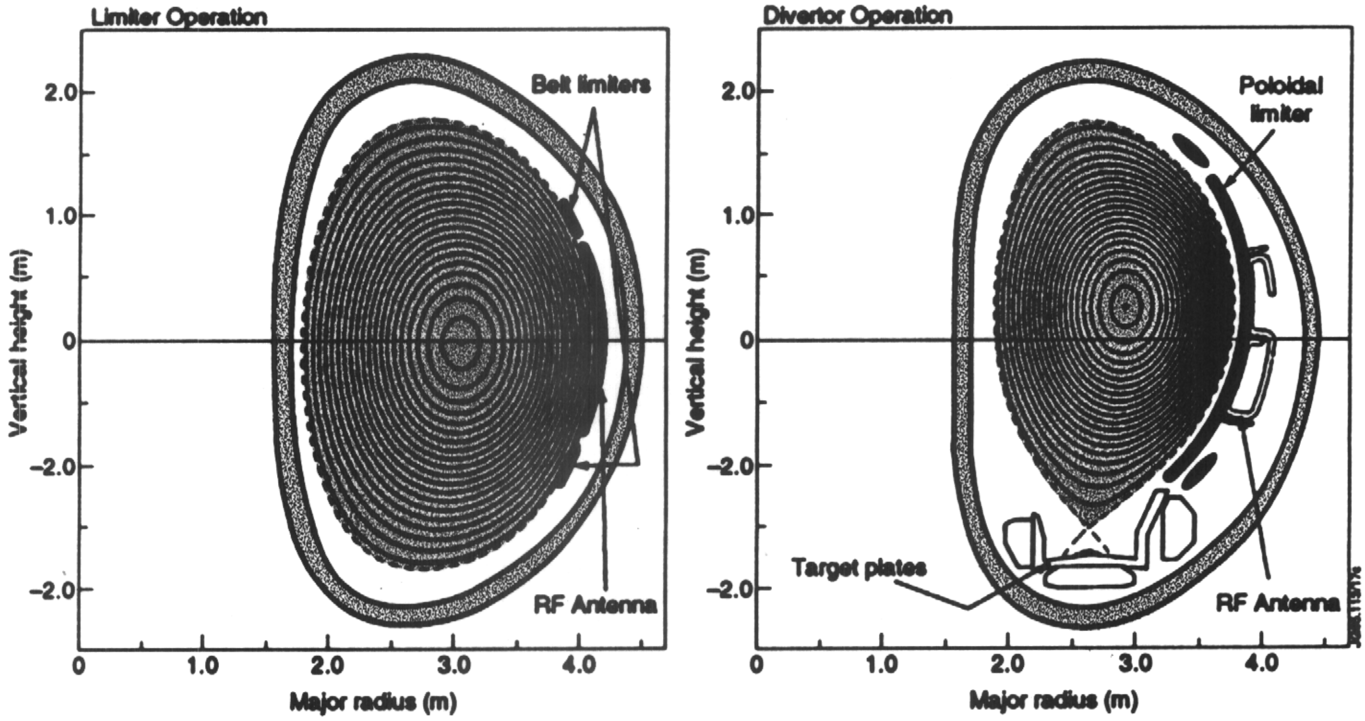
By injecting a mixture of Deuterium and Nitrogen in the plasma, radiation can be enhanced to account for~80% of the power loss from the plasma

WHY A DIVERTOR

- By the end of *1991*, JET results had largely fulfilled the original objectives. However the ***high performance could be maintained transiently***, limited by a combination of MHD instabilities and accumulation of impurities in the X-point region (carbon bloom)

- ***An active control of the impurities*** is needed, and a divertor is the most viable solution for power and particle (including helium ash) exhaust, and for impurity control

- A *divertor* channels the energy and the particle exhaust to *target plates* in a separate chamber where particles can be *pumped* and impurity production can be limited



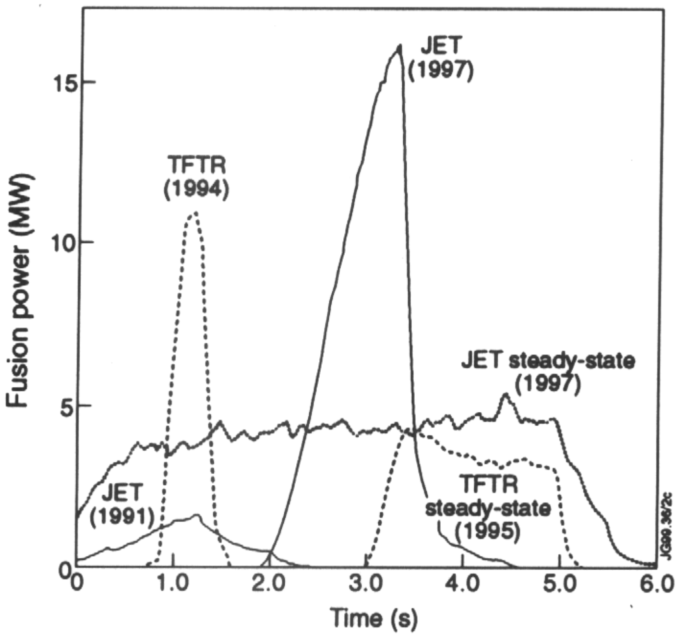
Plasma shape with limiter and with divertor

Deuterium-Tritium Experiment 1

The final quarter of 1997 following months of intensive preparation, saw the fulfilment of the original designers hopes for JET. Using optimal fuel mixtures (50%D–50%T) JET set several world records

The campaign attracted public attention first on September 22nd 1997 when peak powers over 12MW were reached.

On the right of the picture is Dr M Keilhacker, Director of JET from 1992 -June 1999



Numerous successful experiments set records for peak fusion power and fusion energy. Q_{DT} reached 0.9 transiently

MAIN RESULTS IN D-T (1)

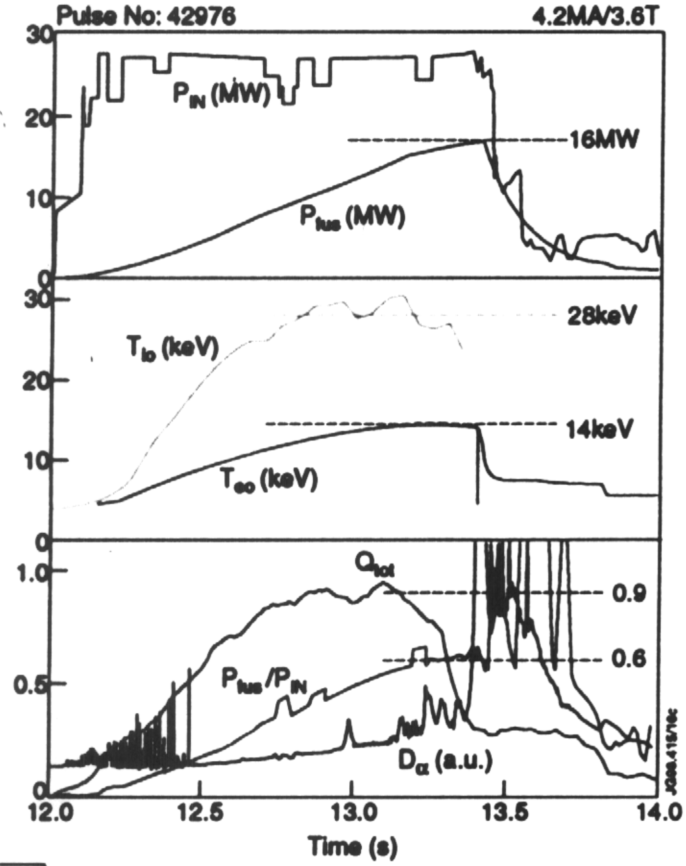
Three scenarios has been extensively studied, reaching record values in plasma performance

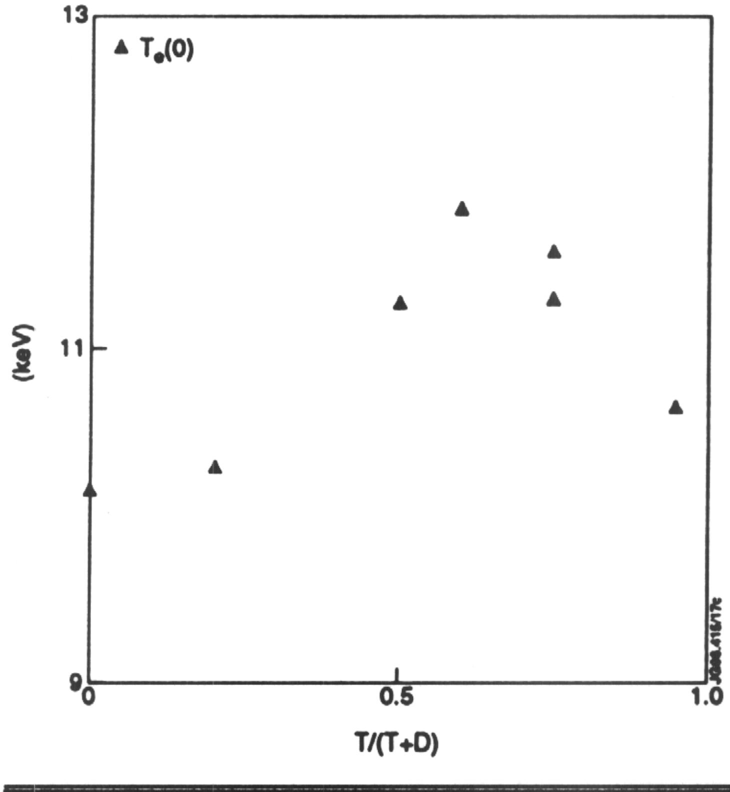
1) ELM-free H-mode:

- *Fusion power*
  - P_F = *16MW*
  - W_F = *13.8MJ*
  - P_{fus}/P_{abs}, = Q = *0.6*
  - Transient Q = *0.9*

I_p = 4.2MA

B_T = 3.6T





- *α-particle heating*

Peaking of Te in the D to T scan at 50-60% indicates α-heating (~1.4keV, ~ 1.5MJ)

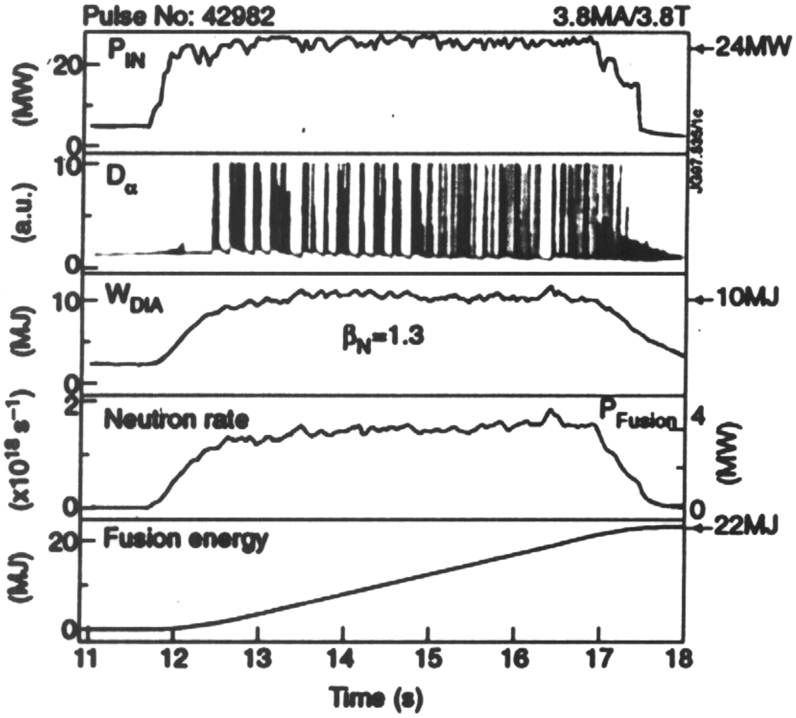
MAIN RESULTS IN D-T (3)

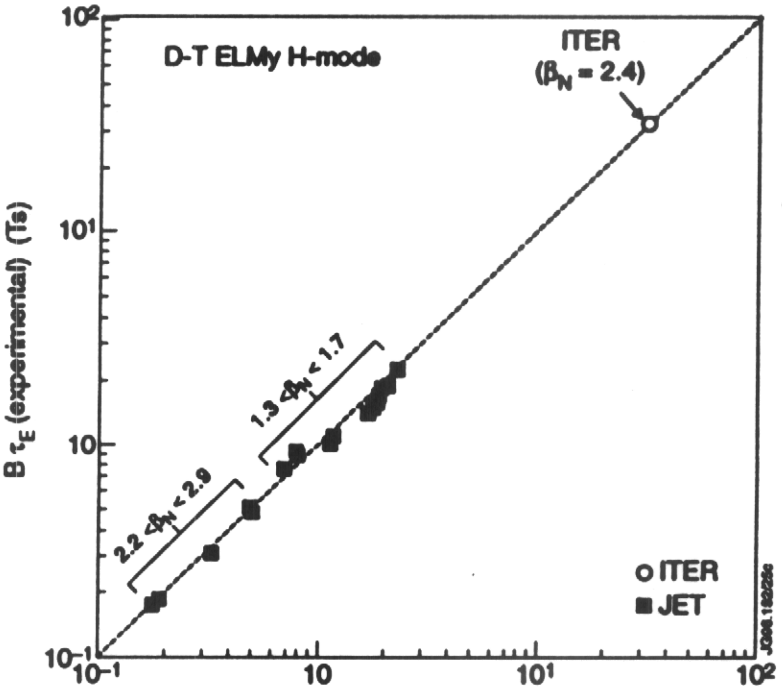
3) ELMy H-mode:

- *Fusion power*
  - P_F = *4.5MW for >5s*
  - W_F = *21.7MJ*
  - Q = *0.2*
  - $T_e \sim T_i$ = *8keV*

I_p = 3.8MA

B_T = 3.8T

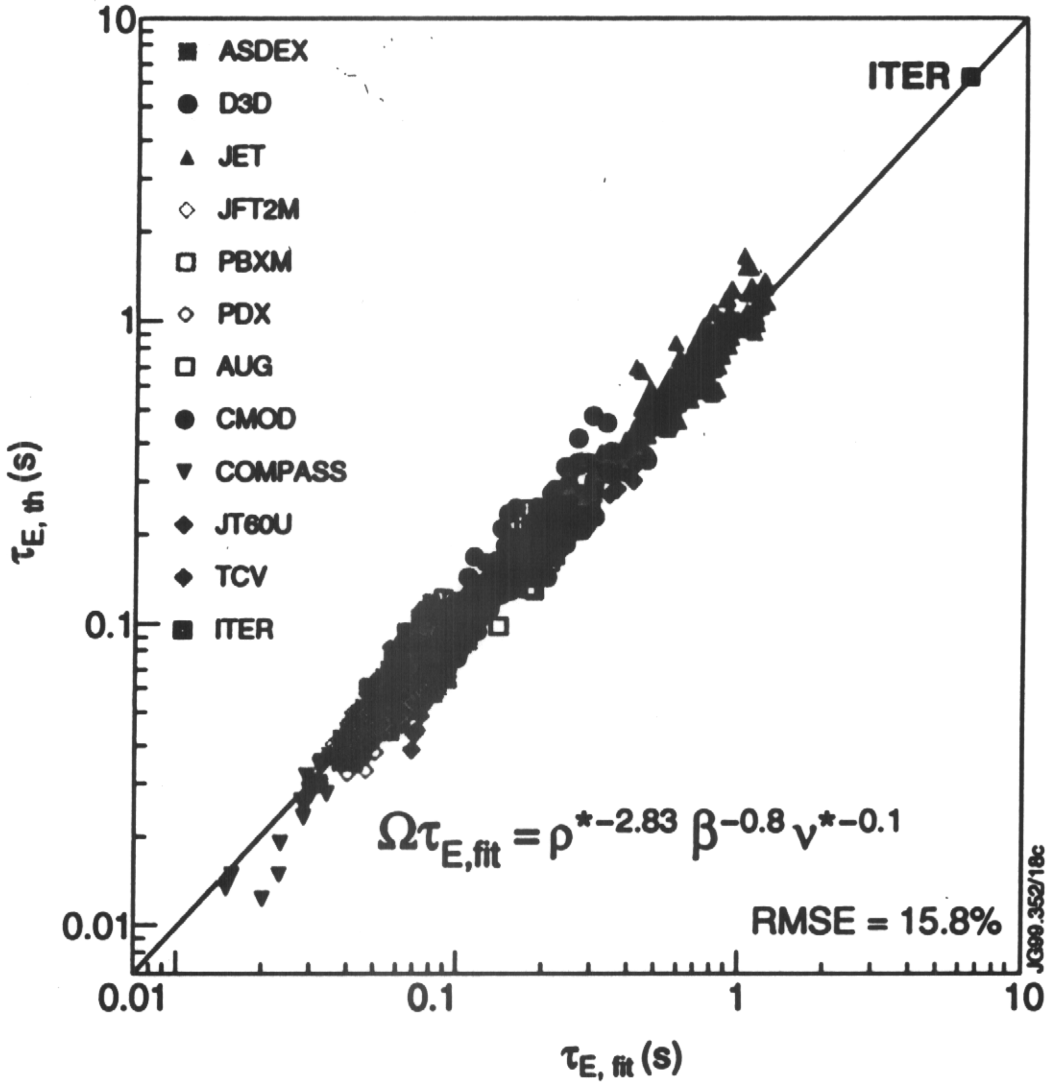




- *ITER similarity pulses (ρ^* scaling)*
  - **Good fit with ITER EPS97 H-mode scaling**
  - **Extrapolates ignition in ITER**

Extrapolation to a Reactor

Scaling laws, derived from experimental data from various tokamaks, are used to extrapolate to reactor conditions



JET is nearest to a reactor, and tritium experiments provide mass scaling

MAIN RESULTS IN D-T (2)

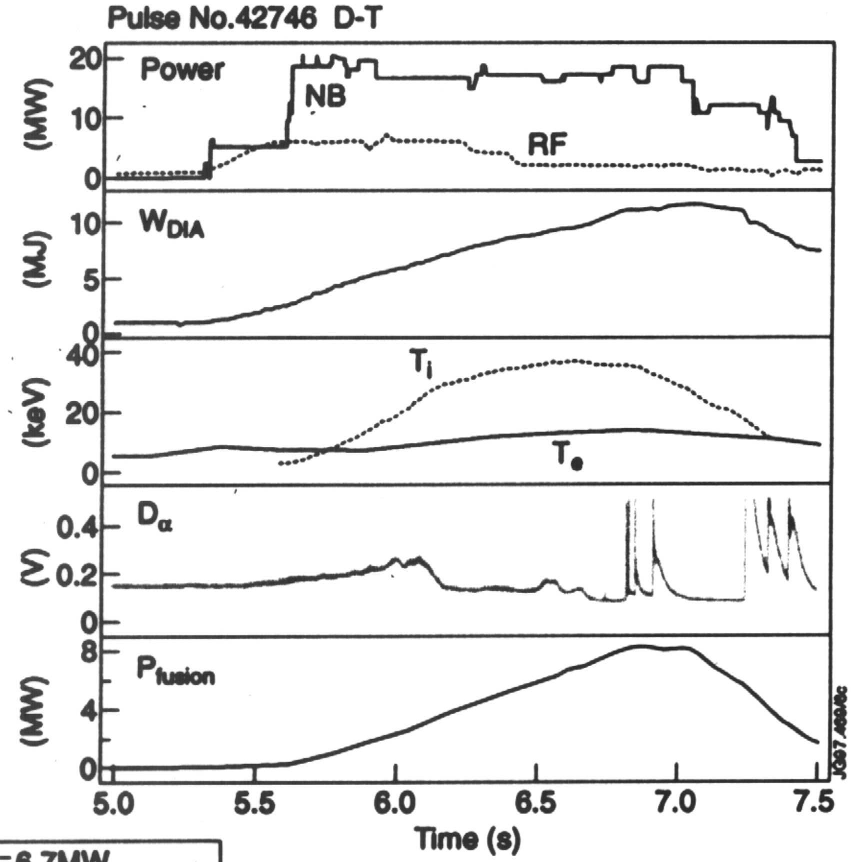
2) Optimised Shear regime:

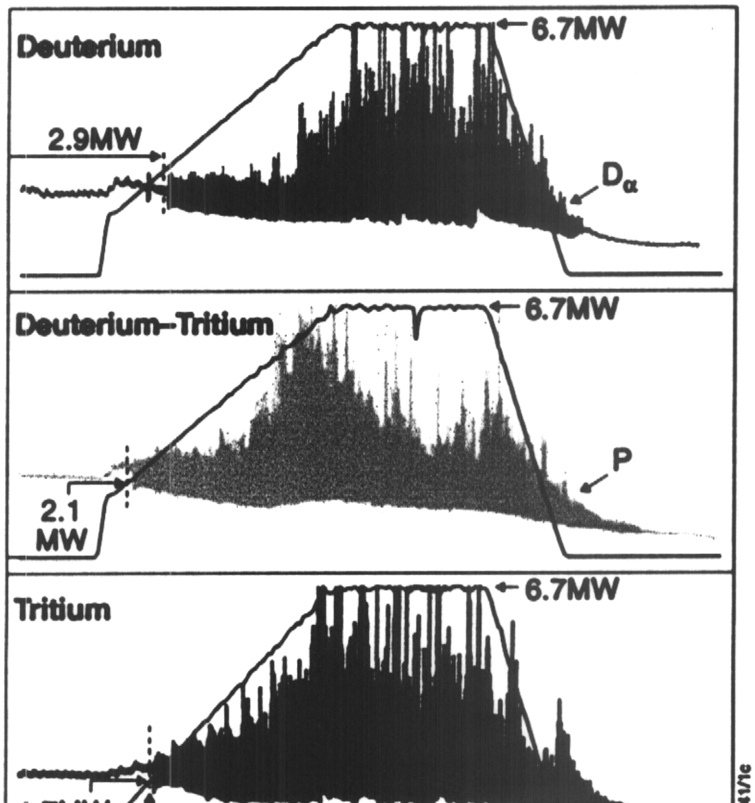
- *Fusion power*

  - PF = *8.2MW*
  - Q = *0.43*

I_p = 3.2MA

B_T = 3.45T

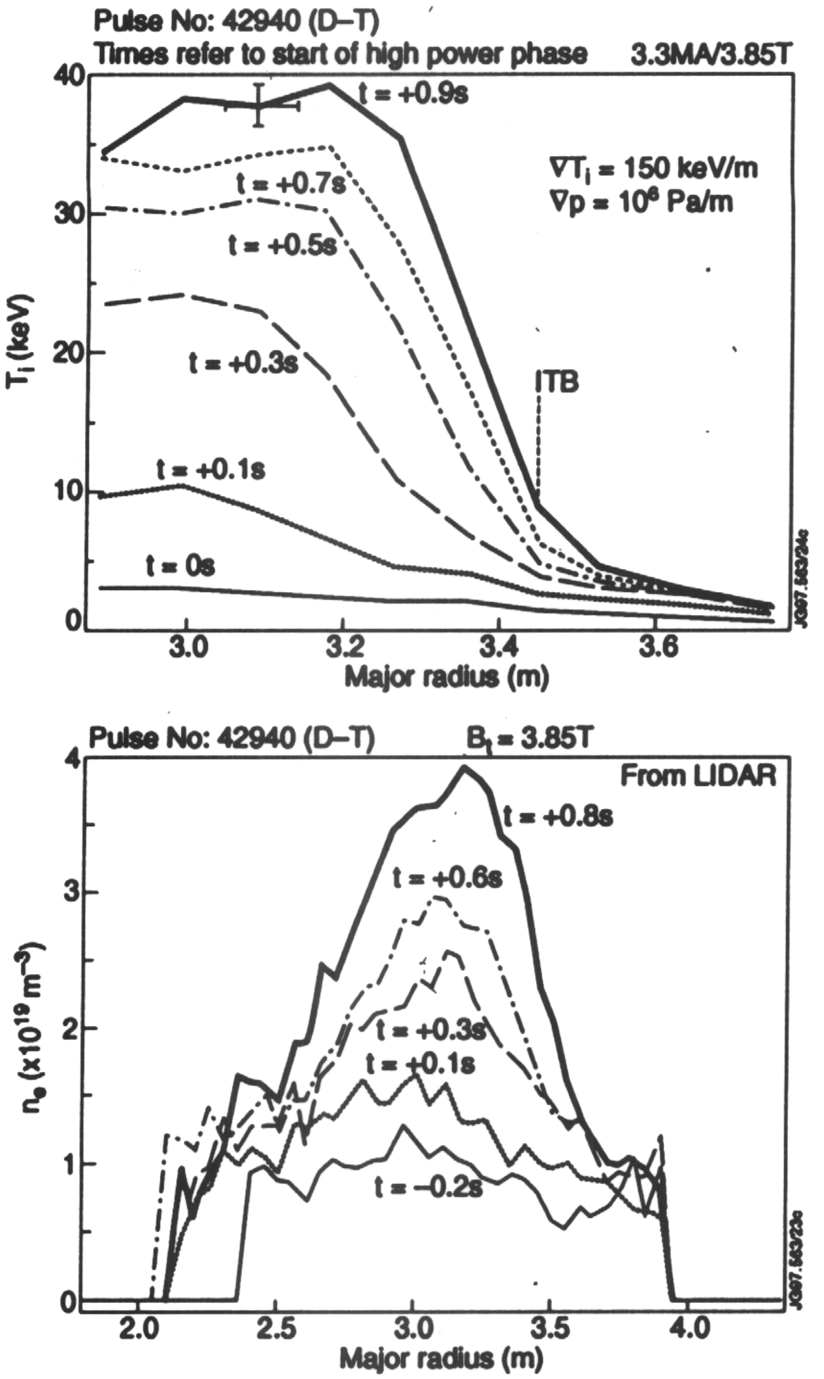




- *L-H transition*

  - Input power for transition in D-T < D-D
  - Therefore, higher performance not achieved, because the H-mode was established too early

Continuous Operation with Internal Transport Barrier



- Substantial increases in density and ion temperature result within the Internal Transport Barrier (ITB).

EUROPEAN FUSION DEVELOPMENT AGREEMENT

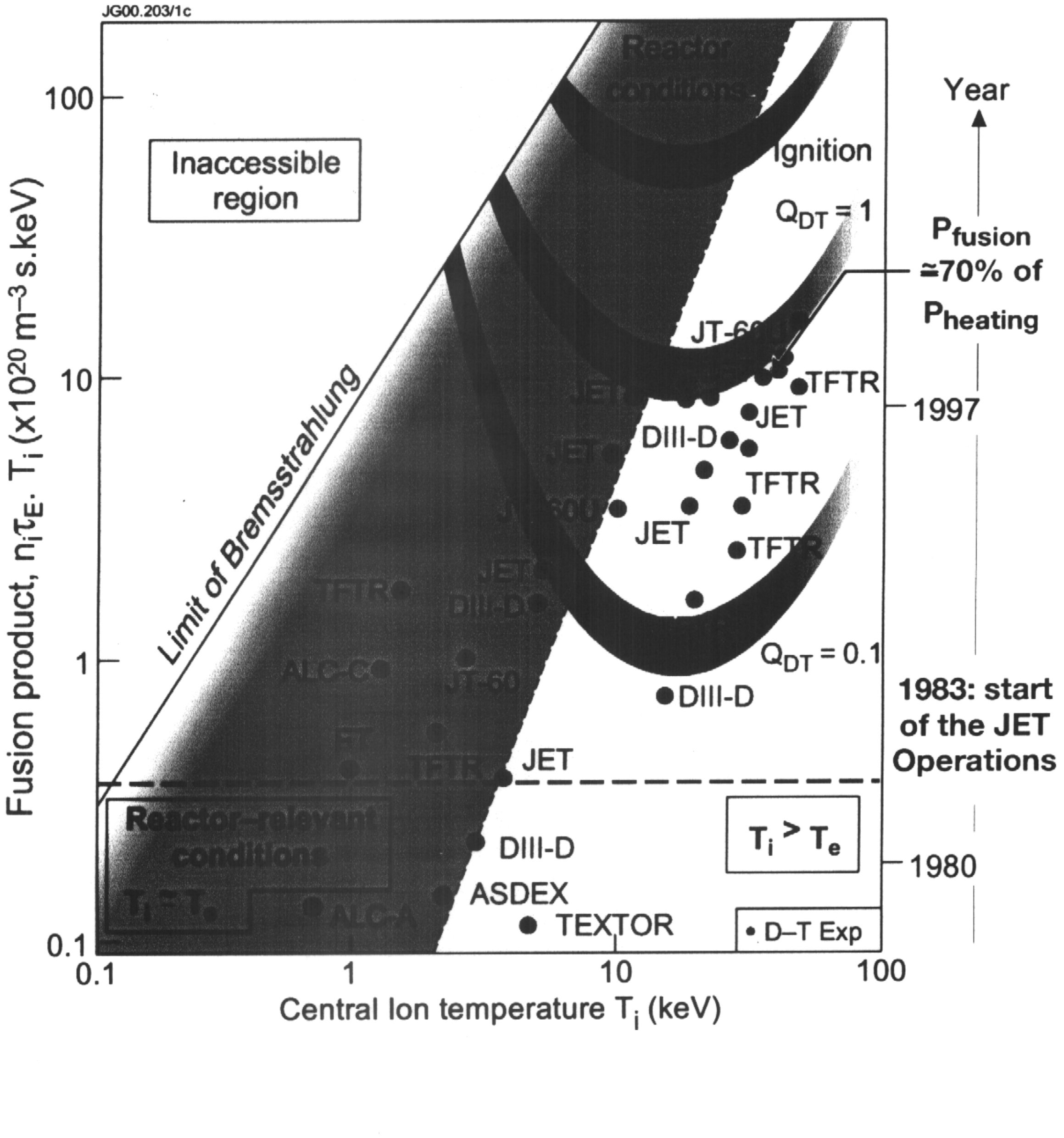
EFDA

JET

The JET Joint Undertaking (3) 1983 - 1999

Progress in global plasma performance

- JET has made a real step forward towards a fusion power reactor. Since its design the fusion product has improved by 25,000 times



- The full potential of the JET facilities remains to be realised

EFDA UKAEA Fusion Working with Europe

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4. New Developments

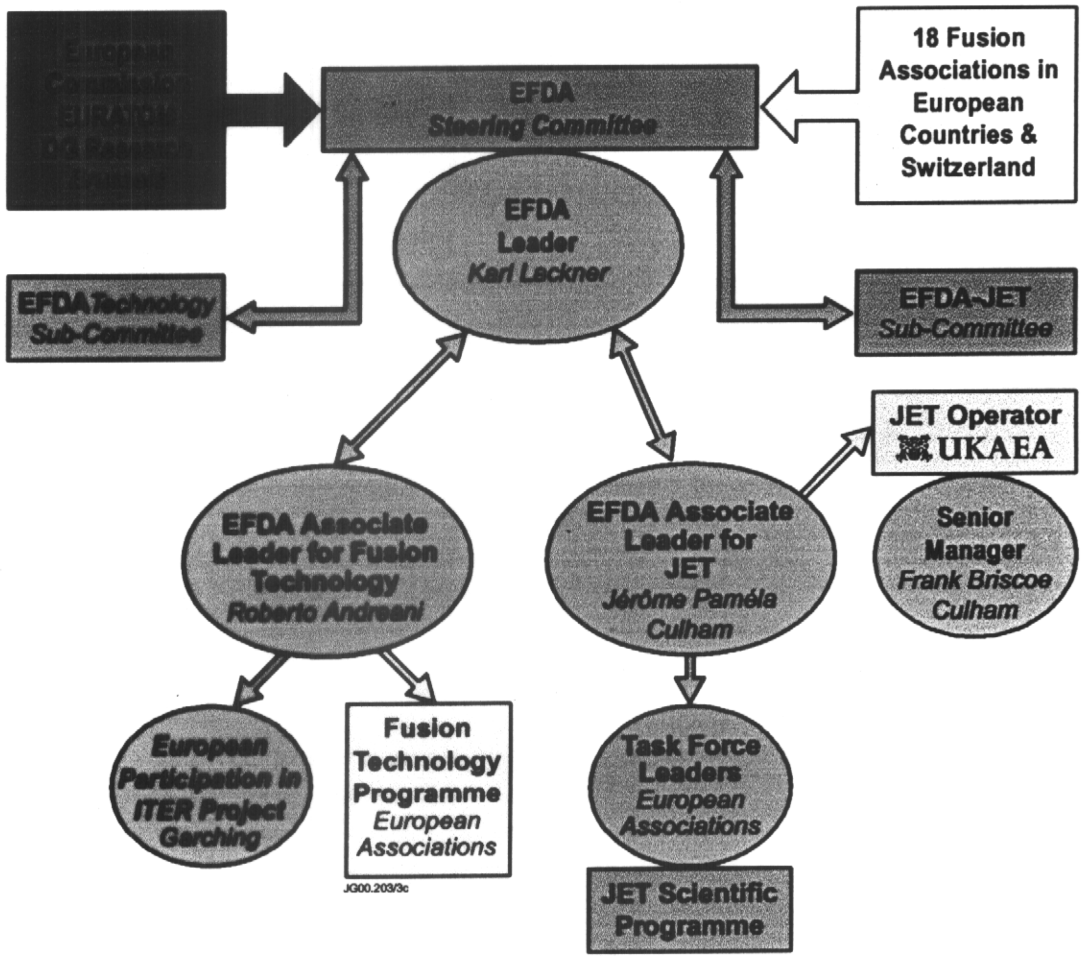
5. ITER Prospects

6. Fusion and EEC Energy Strategy

7. Conclusions

JET within EFDA

(European Fusion Development Agreement)



- JET is run collaboratively within EFDA
- Administered by the the JET Associate Leader's Close Support Unit
- JET Operating Contract undertaken by UKAEA under EFDA
- Experimental Programme planned and executed by Task Forces from the Associations

EFDA UKAEA Fusion Working with Europe

Role of the Euratom/UKAEA Association

EFDA JET Operation Contract

The UKAEA is responsible for the operation and safety of the JET facilities under the terms of the JET Operation Contract (JOC).

The UKAEA Senior Manager is responsible for the execution of JOC:

- Achievement of operational requirements and targets
- Adaptation to the specific requirements of each Work Programme
- Maintenance
- Restart before S/T campaigns
- Installation and commissioning of approved enhancements
- Monitoring of neutrons, activation and contamination
- Assistance to the secondees from the other Associate laboratories

UKAEA Team preparing for restart

EFDA

UKAEA Fusion Working with Europe

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EFDA UROPEAN USION EVELOPMENT GREEMENT JET

EFDA Close Support Unit Culham

The Associate Leader for JET, Jérôme Paméla, has overall responsibility for the implementation of the ***JET Implementing Agreement*** and is responsible to the EFDA–JET Sub-Committee for the execution of the ***JET Work Programme***.

Jérôme Paméla and members of the CSU

The Close Support Unit (CSU) assists him in these duties

- Preparation of the Work Programme and associated Work Plan Budget
- Management of all Orders and Tasks undertaken as part of the Programme
- Management of the JET Operation Contract by the UKAEA
- Co-ordination of contracts with industry for future enhancements of JET
- Monitoring of expenditure and production of Accounts
- Reporting to the EFDA–JET Sub-Committee and EFDA Steering Committee

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EFDA UROPEAN USION EVELOPMENT GREEMENT JET

The JET Development Programme for Enhanced Performance (EP)

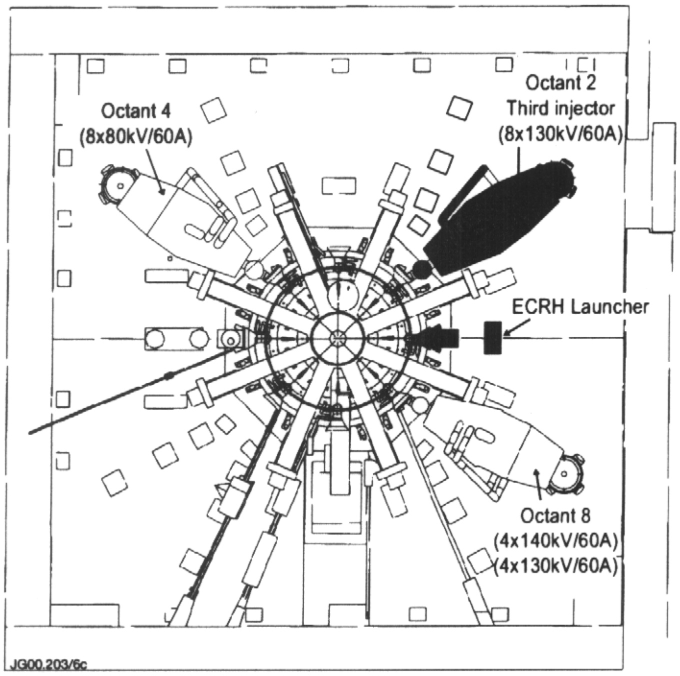
(JET EP)

The ***CCE-FU*** (Consultative EURATOM Committee-Fusion) confirmed that a ***scientific and technical programme*** using the ***JET facilities*** should be carried out beyond the end of the Fifth Framework Programme, with the aim of:

- Consolidating the preparation of base line ***ITER operating scenarios***
- Supporting ***design choices*** in key areas of ***ITER subsystems***, which could be finalised even after the start of ITER construction

This programme should be accomplished with a consequent enhancement of the JET facilities, namely:

- A ***third NB box*** (7.5 to 15 MW); this is in addition to the enhancement of power supplies approved already (7.5MW)
- A new ***ECRH system*** for JET, (5-10MW)
- The development of an ITER relevant ***ICRH antenna*** (8MW of ICRH power)



Additional systems for JET EP are shown in red

EFDA

UKAEA Fusion Working with Europe

JG00.203/15

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- The modification of the Mark II ***divertor*** aiming at ***improved power handling capability***, to cope with a total injected power of about 50MW

In addition ***further ITER relevant activities*** have been recommended, namely:

- Preparation of a proposal to change coverage of the ***first wall*** to using materials such as ***beryllium*** for the wall tiling and ***tungsten*** for the divertor plates

- Retaining the capability of D-T operation, i.e keep the ***D-T plant*** and the ***Remote Handling System*** available, for a possible future D-T campaign

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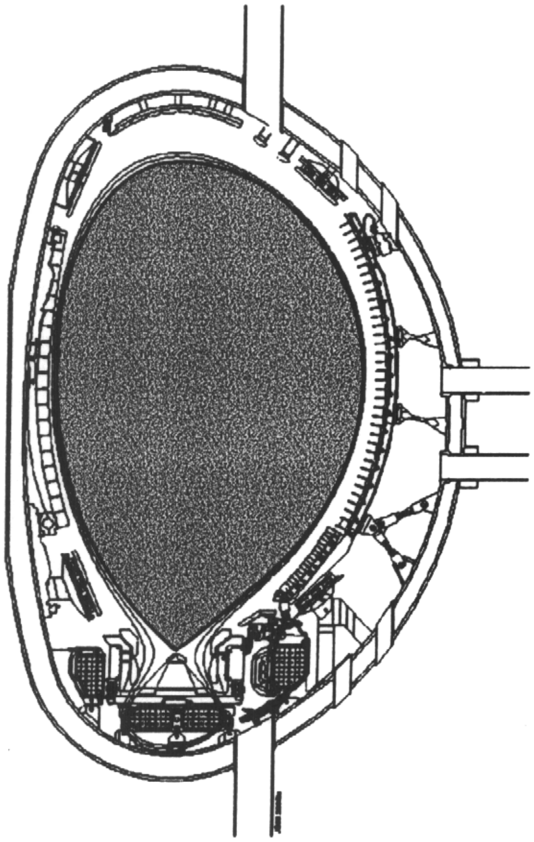
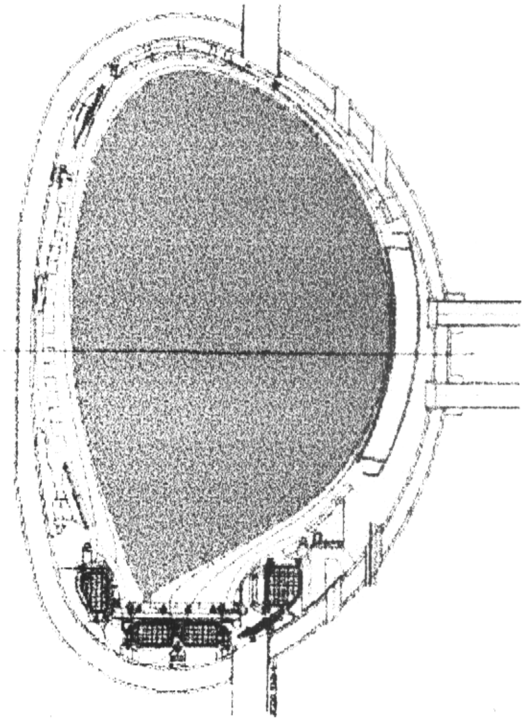
Considered Post 1999 Upgrades (2)



Present Configuration

I_p = 4.0MA
B_T = 3.8T
Vol = 85m³
P_{AH} = 25MW
β_N = 1.3
δ = 0.2
P_{fus} = 4MW (steady state)
P_{fus} = 16MW (peak)



New Configuration

I_p = 6.0MA
B_T = 4.0T
Vol = 106m³
P_{AH} = 50MW
β_N = 1.9
δ = 0.57
P_{fus} = 15MW (steady state)
P_{fus} = 60MW (peak)

JET

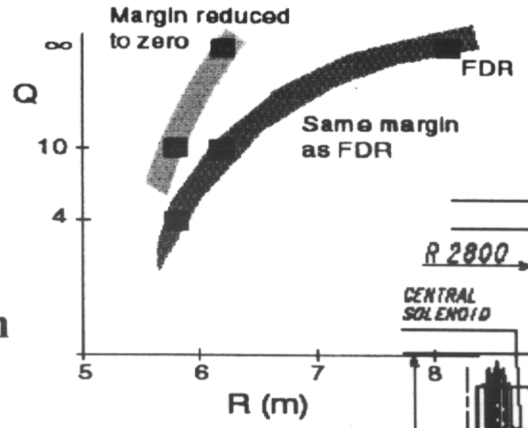
5. ITER Prospects

6. Fusion and EEC Energy Strategy

7. Conclusions

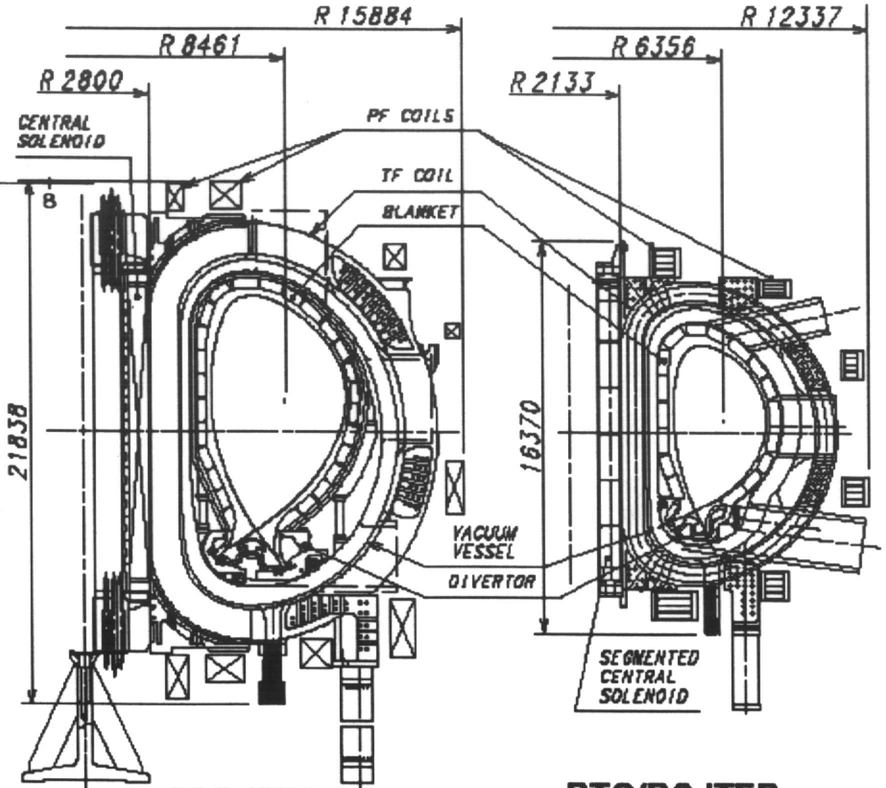
Comparison of ITER-98 with a typical RC-ITER machine

- **In order to reduce the cost by ~ 50% and to achieve Q = 10 a reduction of the machines major radius is reduced from 8.2 m to ~ 6 m**



- **The general concepts for the main machine components remains largely unchanged which allows to make full use of the R&D performed during the EDA**

- **However, a simple downscaling of ITER-98 is not possible !!**



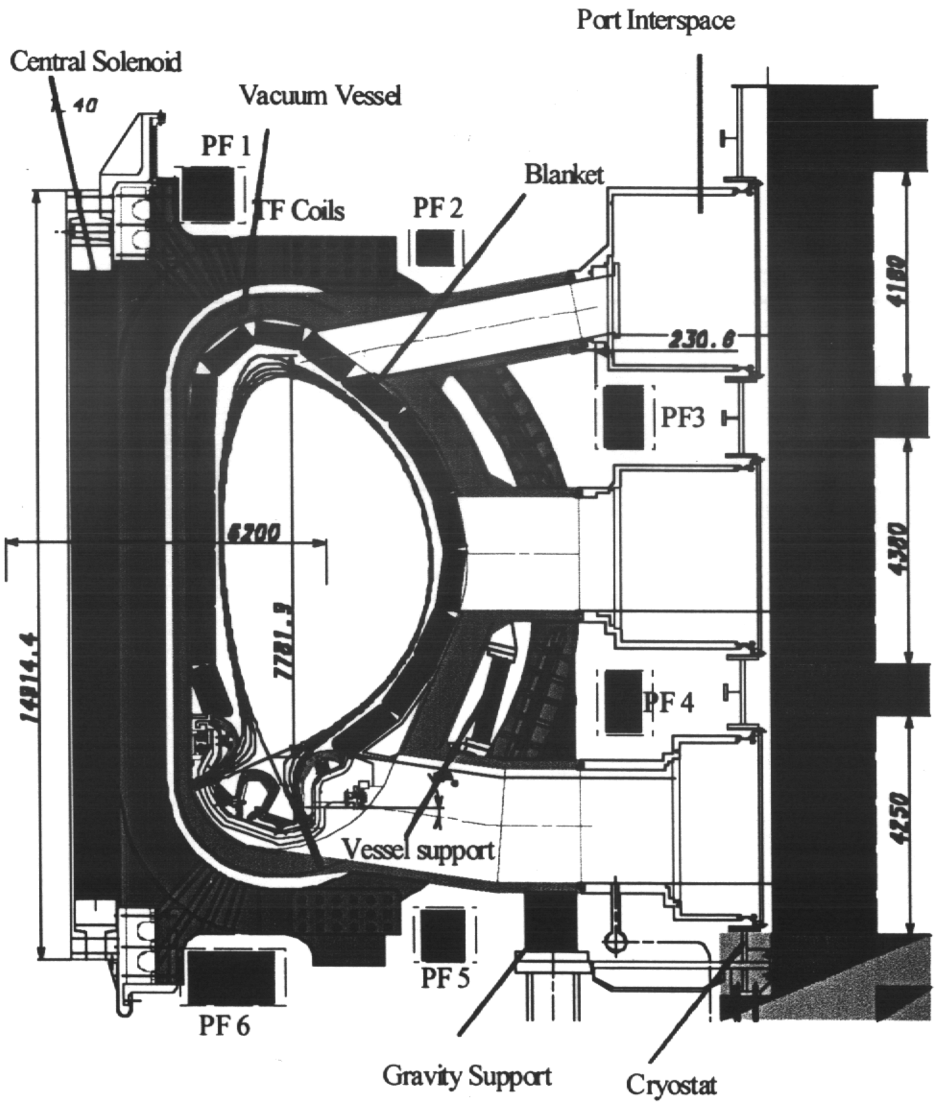
FDR ITER　　RTO/RC ITER

Cross section of ITER-FEAT and machine parameters

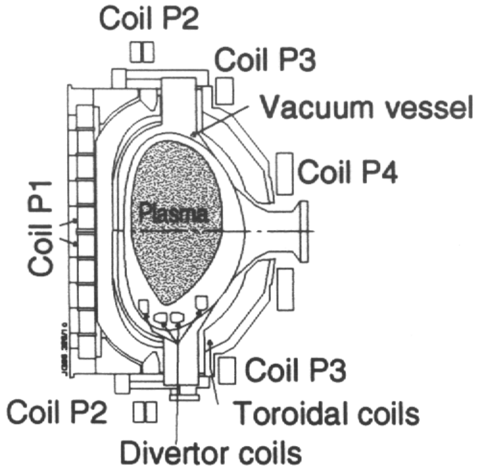
◆ **Parameters of ITER-FEAT**

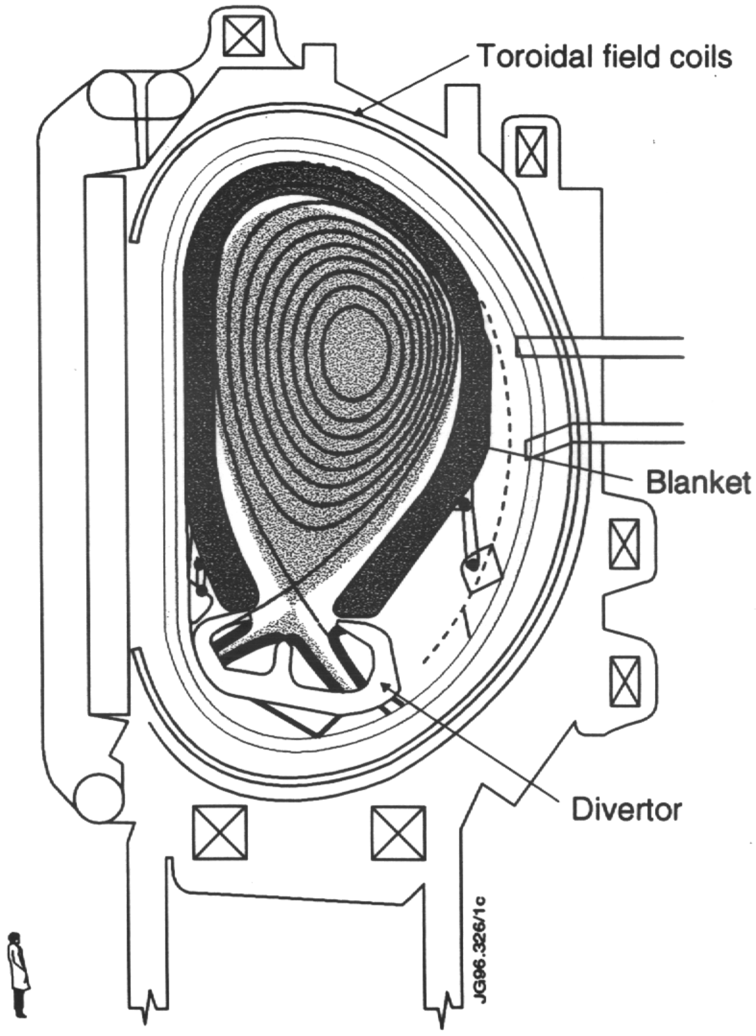
Parameter	Nominal	Max
Major radius, R	6.2 m	<=
Minor radius, a	2.0 m	<=
Plasma current, I_p	15.0 MA	17.4
Additional heating & CD power	73 MW	100
Fusion power	500 MW	700
Toroidal field at major radius, Bo	5.3 T	<=
Elongation at 95% flux, $\kappa_{95,}\ \kappa_X$	1.7, 1.85	<=
Triangularity at 95% flux, $\delta_{95,}\ \delta_X$	0.33/0.49	<=
Plasma volume	837 m^3	<=
Plasma surface	678 m^3	<=
MHD safety factor at 95% flux, q_{95}	3	2.6
Average neutron wall load	0.57 MW /m^2	0.80

Inductive pulse length ~ 400 sec



Poloidal Cross-sections of JET and ITER





JET

R = 3m; I = 6MA

ITER

R = 8.14m; I = 21MA

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Status of ITER

The original design of ITER was completed in June 1998, when the USA decided to abandon the Project

EU, Japan and Russia decided to review the design and the objectives of ITER, aiming at reducing the cost by~ 2 (from ~ 6 B$, to ~ 3B$ at 1989 value)

The new design, called ITER-FEAT should be completed by June 2002

Negotiations are underway on the organisational structure for construction, on the site requirements and on the repartition of financial contributions between Partners

There are preliminary proposals for a Site in Japan, in Canada and in Europe (Cadarache)

But…nobody is putting money on the table yet

6. Fusion and EEC Energy Strategy

7. Conclusions

The Green Book [1]

Last December Mrs Loyola de Palacio, Commissioner for Transport and Energy and Vice-President of the European Commission presented to the European Parliament the Green Book on European Energy Strategy approved by the Commission

The Green Book gives a comprehensive picture of the various energy options and mixtures, including nuclear energy (which today accounts for 33% of the elecricity poduced in the EEC)

There is a clear stetement concerning nuclear energy: "Without nuclear energy it is impossible to meet the Kyoto requirements for the environment"

The Green Book [2]

"We have to convince the public opinion to continue and develop further nuclear energy, waiting for nuclear fusion, the ultimate source of energy, practically inexhaustible and environmentally friendly"

While the outcome of the debate in the European Parliament is not available yet, the above statement has given a boost to the decision making process about ITER

It is the first time world-wide that a politician with responsibility in energy policies, writes and speaks in this way about nuclear fission and nuclear fusion.

Therefore, let's hope!

Conclusions

With its unique combination of divertor configuration, heating and profile control systems, tritium capability and associated nuclear fusion technologies, JET will remain for the years to come the most valuable machine in support to ITER

ITER FEAT design is being completed and negotiations for constructions among the Partners (at present Europe, Japan and Russia) are underway

The Green Book on energy issued by the Commission gives a comprehensive energy strategy for Europe, including nuclear fission and, in due course, nuclear fusion