JOINT EUROPEAN TORUS

JET–P(87)59

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JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

Preprint of a paper presented at the EPS General Meeting (EPS-7), Helsinki, Finland,
10th August – 14th August 1987

JET AND THE PROSPECT FOR NUCLEAR FUSION

R.J.Bickerton

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA, U.K.

KEYWORDS: Tokamak, Ignition, L-mode and H-mode confinement.

ABSTRACT

This paper describes the Joint European Torus (JET) device which was built as a European collaboration effort, with the aim of testing the scientific feasibility of producing controlled thermonuclear reactions between light nuclei with a net yield of energy.

JET is the largest magnetic confinement machine in the world both in physical size and in the magnitude of the plasma current ($5x10^6$ Amperes). The machine came into operation in mid 1983 and has followed the first stages of a planned evolution, in which the performance is progressively increased mainly by adding more heating power and which will culminate in eventual operation in a deuterium-tritium mixture. This will permit study of the plasma performance when there is a substantial power input from the α-particle fusion products. So far operating in deuterium gas with 8MW of additional heating by neutral beams, a peak ion temperature of 12keV has been obtained with a corresponding fusion product (density x confinement time) of $8x10^{18}m^{-3}s$. If the same conditions were to be achieved in a deuterium-tritium mixture, then the ratio of thermonuclear power output to the heating power input, Q, would

be $\sim$ 0.1. It is expected that following further technical improvements to JET, "scientific breakthrough" (namely Q=1) will be achieved.

The next step after JET will be to study a burning or ignited plasma in which no power input is required because energy losses are balanced by α-particle heating. The requirements for such an experiment will become increasingly clear as more data is obtained from JET. At present it seems likely that a larger apparatus will be needed with a plasma current capability of 12-15MA. These requirements for the thermonuclear furnace remain broadly consistent with the known technological constraints on an eventual power reactor.

1. Introduction

The aim of the fusion research programme is to find out if it is possible in a controlled and potentially useful way to create high temperature matter in which thermonuclear fusion reactions between light nuclei can produce a net yield of energy. The most favoured reaction is that between deuterium and tritium,

$$D + T \rightarrow {}^{4}He + n + 17.6\ MeV$$

The cross-section rises to a peak of 5 barns at a deuteron energy of 120keV, making it the least demanding reaction in terms of the conditions required for a net energy gain. Because fusion reactions occur between charged nuclei and because the fusion cross-sections are much smaller than the Coulomb cross-section for scattering, it follows that to achieve a net energy gain requires a hot gas with a temperature for the D-T case of $\sim$ 10keV ($\sim 10^{8}$°K). A gas at this temperature is fully ionised and as such constitutes a plasma with closely equal number densities of electrons and ions.

Lawson [1] first enunciated clearly the additional condition that must be satisfied for net power production, namely (for D-T),

$$n \tau_\varepsilon > 2 \times 10^{20} \, m^{-3} s.$$

Where the energy confinement time τ_ε is defined by

$$\tau_\varepsilon = \frac{W}{L}$$

where W is the energy content of the plasma and L the power loss by convection, conduction and radiation.

Such a hot gas must clearly be kept away from material walls, maintained in pressure equilibrium and thermally insulated. This can be done by magnetic confinement, with an isotropic plasma pressure p, we then require that

$$\bar{j} \wedge \bar{B} = \nabla p$$

where $\bar{j}$ and $\bar{B}$ are the local current density and magnetic field strength in the plasma. With div $\bar{B} = 0$ it follows from a theorem by Poincaré [2] that the system must be topologically toroidal. The tokamak is such a system which is symmetric about the major axis of the toroid and in which the required confining magnetic field is produced by the combination of a toroidal current in the plasma itself and currents in external coils [3]. The tokamak is the most advanced of several classes of toroidal magnetic confinement systems. It was pioneered in the Soviet Union in the 1960's. There are now many of these machines around the world with very different sizes and research aims.

2. JET

The Joint European Torus (JET) is a large tokamak with the following aims; to study

i) scaling of plasma behaviour as parameters approach the reactor regime,

ii) plasma-wall interactions under near-reactor conditions,

iii) plasma heating methods

iv) α-particle production, confinement and consequent plasma heating.

The last aim requires that the machine be eventually operated with a deuterium-tritium plasma. The machine has therefore been designed from the start with provision for remote-handling and for tritium handling.

Table 1 lists the main parameters of JET while figure 1 shows an artist's impression of the machine. The machine was built on schedule and to budget in the five years from mid-1978 to mid-1983. Since June 1983, the machine has been operated with scheduled shut-down periods for the foreseen upgrading of the machine, particularly in the increase of the plasma heating equipment and power-handling elements inside the vacuum vessel.

The electrical conductivity of a hot plasma is proportional to $T_e^{3/2}$, where T_e is the temperature of the electrons. Consequently the ohmic power input due to the current flow through the plasma falls as the temperature rises and is inadequate to heat the JET plasma sufficiently for our purpose. Two additional heating techniques have been used. The first is ion cyclotron resonance heating [4] in which radio frequency power is fed into the plasma at a frequency (25-55MHz) corresponding to the cyclotron frequency of a chosen ion species in the plasma core. In the experiments reported here, up to three launching antennae have been used to feed up to 8MW into the plasma for pulse times of 2–3 seconds. The second technique is that of neutral beam injection [5] in which powerful beams of high energy neutral atoms (∿ 80keV) are injected into the plasma. The fast neutrals cross the confining magnetic fields but are ionised by collisional processes when they enter the plasma. The resulting trapped fast ions then slow down giving their energy to the background plasma ions and electrons through Coulomb collisions. In the experiments reported here, up to 10MW of power was injected using 80keV deuterium neutral beams, again with pulse lengths of several seconds.

3. Operating Limits

JET has proved to have certain operating limits, in terms of normalised current and electron density very similar to those for smaller tokamaks. The normalised parameters are the inverse safety factor,

$$\frac{1}{q} = \frac{\pi R}{5A} \; \frac{I}{B}$$

where R is the major radius of the plasma (m), A the cross-section area of the plasma (m^2), I the plasma current (MA) and B the toroidal field strength (T). q is approximately the number of times a magnetic field line at the plasma boundary passes around the major axis of the toroid in spiralling once around the minor axis. For the density, the parameter M is,

$$M = \frac{\bar{n} R}{B} \quad (\times\ 10^{19}\ m^{-2}\ T^{-1})$$

where $\bar{n}$ is the average electron density in units of $10^{19} m^{-3}$. Figure 2 shows stable JET operating points in the $\frac{1}{q}$ vs M plane. The stable operating regime is bounded both at high current and high density by disruptive instabilities in which plasma confinement is rapidly lost and the plasma current falls uncontrollably to zero. Detailed analysis shows that the high density disruptions are due to increased radiation losses from the outer plasma regions leading to a contraction of the current channel [6]. The disruptions at high current are due to the boundary value of q approaching the sensitive rational value of 2. The lines on figure 2 delineate the density limits with ohmic heating alone, with RF and with neutral beam heating. It is interesting that the additional RF power does not change the ohmic limit, while additional power from beams makes an increase of nearly 70% possible. The reason for this has not been clearly established, but it is probably related to the fact that beam heating also fuels the central core of the plasma which RF heating does not. Another important and possibly decisive factor is that RF heating increases the plasma density at the plasma edge. Finally, we note that the maximum value of M in JET is $\sim$ 6 while for a planned next step ignition experiment M $\sim$ 16 is required [7].

4. Operating Modes

The machine can be operated in different modes as far as the plasma boundary is concerned. Figure 3 shows the normal mode in which the plasma boundary is determined by the intersection of the closed magnetic surfaces by a material (carbon) limiter on the mid-plane, (in fact, there are 8 such limiters in the experiments reported). Alternatively, the poloidal field determined by external coils can be adjusted so that the plasma is bounded by a magnetic separatrix with either a symmetrical double-null arrangement or just a single-null (figure 4). In the case of a magnetic separatrix, the plasma diffuses across the separatrix and then flows along field lines to the top and/or bottom of the vacuum vessel. At the separatrix, the value of $q \to \infty$ so that there is a layer inside the separatrix of high magnetic shear, ie of rapidly changing q with radius. As we will see later magnetic separatrix operation can, under some conditions, give a dramatic improvement in the energy confinement time [8].

5. Diagnostics

It is clearly important to have accurate and reliable measurements of plasma conditions. Except at the extreme edge of the plasma material probes cannot be used. Therefore we use either passive methods to analyse radiation and particle emission from the plasma or active methods where radiation or particles from an external source are used to probe the plasma. For JET, there are now about 35 major systems [9] to determine the plasma shape, plasma current, loop voltage, electron density profile, electron and ion temperature profiles, neutron yield and spectrum, impurity content, radiation loss, interaction with walls and limiters etc. The diagnostics are adequate to characterise, with fair accuracy, the main properties of the discharge. They do not enable us to measure in detail the processes which determine the degree of plasma confinement. This is not peculiar to JET, the required diagnostic performance has yet to be achieved in any tokamak.

6. JET Pulses

Figure 5 shows the time dependence of plasma current, loop voltage and plasma density for a discharge with ohmic heating only. Notable is the long flat top time of ∿ 8s at a current of 3.6MA, the low loop voltage ∿ 1 volt/turn and the slowly rising density. Figure 6 shows the electron and ion temperatures for the same pulse as measured by various diagnostic techniques. The high sampling rate between 7 and 9 seconds for the central electron temperature reveals the fluctuations due to the central "sawtooth" instabilities in the plasma. This pulse is one with a high energy confinement time τ_ε.

$$\tau_\varepsilon = W/(P - dW/dt)$$

where W is the energy content in the plasma, P the total input power and dW/dt is the time derivative of the plasma energy. For most of the quoted JET data, τ_ε is measured during the flat-top when $dW/dt \ll P$. The value of W can be obtained by integrating the measured profiles of density and temperature, alternatively it can be obtained by two types of analysis of the magnetic fields. The three methods give good agreement.

7. Confinement Time

With Ohmic heating only and discharge currents up to 5MA the energy confinement time scaled approximately as

$$\tau_\varepsilon = \text{constant} \times \bar{n}\, q\, R^2\, a$$

with some saturation at the highest values of $\bar{n}$. The scaling with physical size was essentially established by comparison with smaller experiments [10]. The absolute values of τ_ε reached 0.8-1.0s. These record values reflect the large physical size of JET.

However, with the application of additional heating, the confinement time is degraded in approximately the same way for both neutral beams and ion cyclotron resonance heating. Figure 7 shows the data for τ_E versus power input(P) for a wide range of JET discharges. The data points are divided only according to the level of plasma current. The continuous lines are the predictions of an entirely empirical scaling [11] which was obtained from tokamaks with approximately one third of the JET length scale and one tenth of the maximum current. In view of this extrapolation, the agreement is remarkable. This scaling has been called L(for low)-mode to contrast it with the H-mode (for high).

The H-mode was first discovered on ASDEX where with magnetic separatrix bounded plasmas and above a certain threshold neutral beam heating power, the discharge changed into a new operating mode with increased density, flatter electron temperature and density profiles and greatly improved energy confinement times. These favourable results were confirmed on other machines with separatrix-bounded plasmas including devices without special arrangements to receive the diverted plasma outflow. These results encouraged the search for similar phenomena on JET.

Finally, such a transition to the H-mode was achieved with neutral beam injection into JET. Figure 8 shows the relevant traces, in which the transition is marked by a discontinuous increase in the energy content, a rise in the edge electron temperature and a fall in the D_α signal which reflects the recycling of particles at the wall. The density rises continuously during this particular H-mode and the discharge reverts to the L-mode when the radiated power reaches too high a level. Most of the JET H-modes are of this transient character but, in some cases, quasi-steady state conditions have been reached accompanied by periodic edge localised instabilities in the boundary.

Figure 9 shows τ_ε versus P for H-modes with currents of 1,2 and 3MA. The continuous lines are again from the Goldston scaling but with the constant increased by a factor 2. This plot shows that the degradation with power still persists but with a very important improvement in magnitude over the L-mode. In the ASDEX case, the confinement is broadly restored to the ohmic value and does not degrade with power. This point and the achievement of steady states will be the subject of an intensive experimental study in the next JET campaign.

8. Fusion Q

The single parameter which characterises progress in this field is,

$$Q = \frac{\text{Thermonuclear Power Out}}{\text{Power Input}} = P_{th}/P_{in}$$

This tends to infinity, when the plasma reaches ignition, the power lost from the plasma then being balanced by the α-particle power deposited in it. In a power reactor the neutrons lost from the plasma would be captured in an external blanket.

$$P_{th} = \int dV \; n_D n_T (\overline{\sigma v}) \; \Upsilon$$

where $\overline{\sigma v}$ is the fusion cross-section ion velocity product averaged over a Maxwellian distribution for temperature T, and Υ is the energy yield per reaction. Taking into account the full data on $\overline{\sigma v}$, assuming profiles for density and temperature typical of those in JET, the contours of constant Q can be plotted in the plane $\hat{n}_D \tau_\varepsilon \hat{T}_i$ versus T_i ($\wedge$ denotes central values). The advantage of this representation is that it is very insensitive to profiles for the ion temperature range of interest namely 7–20keV.

Figure 10 shows the JET experimental data plotted in this plane where the volume integral has been limited to the 30cms radius of the discharge core. To the right of the line marked, the equipartition time for energy exchange between electrons and ions is longer than the energy confinement time so that it is possible to have $T_i > T_e$, if the additional heating method gives power preferentially to the ions. This is the case for the high ion temperature (>10keV) 3MA points, where typically $T_i \sim 2T_e$. Evidently, the highest values of Q ($\sim$0.1) are achieved either in these "hot ion modes" or in the 2 and 3MA H-modes as represented by the open symbols. The data shows a clear improvement of $\hat{n}\,\tau_\varepsilon\,\hat{T}_i$ with current. Note that the experimental points are for a deuterium plasma which in fact contains a few percent of both carbon and oxygen impurities. The values of deuteron density take this into account, (typically $\hat{n}_D \sim 0.5\hat{n}_e$). The D-T performance in terms of Q is calculated by then assuming $\hat{n}_D = \hat{n}_T = (\hat{n}_D)/2$ where (n_D) is the present experimental value.

9. Extrapolated JET Performance

The major changes to JET, which have largely been already made should permit,

a) Limiter operation at 7MA

b) Single-null X-point operation at 4MA

c) Increase of neutral beam heating power to 20MW (from 10MW)

d) Increase of ion cyclotron resonance heating power into the torus to 20MW (from 8MW)

Taking the L-mode scaling and the increased input power, the energy confinement time predicted for 7MA is $\sim$ 350ms. Taking the H-mode as giving 2 x the L-mode value the confinement time at 4MA should be $\sim$ 400ms. Figure 11 shows the calculated Q values versus average density for fixed confinement times of 400 and 600ms. In each case, the thermonuclear Q is supplemented to a significant degree by the contribution from fusion reactions between the fast injected ions and the background - the so called beam-plasma reactions. The curves peak at a given density because that gives the optimum temperature. The calculations make no allowance for the depletion due to impurities. It is evident that with $\tau_\varepsilon \sim 0.4$s a total Q $\sim$ 0.7 should be achievable. The resulting additional α-particle power of $\sim$ 6MW deposited into the plasma should be detectable.

10. Extrapolation to an Ignition Machine

It is clear that the next step after JET must be to create an ignited plasma in which $Q = \infty$. Only in this way can the problems of a sustained burn be studied. Such a plasma also provides an abundant source for 14MeV neutrons with which to study a number of related technical problems.

In the light of JET results, an ignition experiment should be designed to operate in the H-mode with a single null. The best estimate for the confinement performance is then 2 x the L-mode value. The European NET team has produced a number of design studies for such a machine [6]. If we take the parameters of what they term "enhanced" NET, namely

$$R = 5.4\text{m}, \quad \varepsilon = 1.7, \quad I_p = 14.8\text{MA}, \quad a = 1.7\text{m}, \quad B = 4.8\text{T},$$

we find that it will ignite with an additional heating power of 100MW and a realistic value of M $\sim$ 8. After ignition, it may be possible to increase M (ie the density) to the planned operating point M $\sim$ 16 giving 1GW of fusion power. The standard versions of NET in which more of the volume inside the toroidal field coils is taken up by blanket and shield and which consequently have lower plasma parameters (eg I $\sim$ 10MA) would not ignite. However the difference is small, $\sim$ 40% in $\hat{n}\, \tau_\varepsilon \hat{T}_i$ and could perhaps be found by other measures, in particular by profile optimisation.

11. Confinement Physics

The extensive use of empirical scaling data results from the fact that we do not have a full understanding of the physics determining both the energy and particle loss rates from the plasma. The experimental confinement times are typically one to two orders of magnitude shorter than those predicted for binary collisions in a stable plasma [12]. This is not surprising, because according to linear perturbation theory, the plasma should be unstable to a variety of fine scale modes. However, we have on the one hand no fully satisfactory theory with which to predict the non-linear consequences of such instabilities and on the other we do not have the diagnostic capability to measure directly the fluctuations in magnetic field, electron density, electric field and their correlations.

The likely instabilities fall into two main classes, drift waves in which fluctuating electric fields perpendicular to the magnetic field cause oscillations of the plasma and magnetohydrodynamic modes which may cause a break up of the confining magnetic field structure. In this latter case the loss mechanism for heat may be simply flow of electrons along the magnetic lines. Because the classical electron thermal conductivity along the lines is typically 10^{12} times the perpendicular conductivity under JET conditions, it is clear that only a small random radial component of magnetic field is required to give significant transport [13] [14].

Many authors starting with Coppi [15], have noticed a remarkable constancy of the form of the electron temperature profile in tokamaks, largely independent of the profile of additional heating power deposition. If this is strictly true then the concept of a local thermal conductivity is invalid and the tokamak column has some degree of self organisation. A possible explanation has been given [16] in terms of relaxation to a minimum energy state subject to certain constraints.

All these matters are still controversial and great efforts are being made to improve both the theory and the diagnostics. The TEXT tokamak in Texas is particularly notable in this context since it is devoted to gaining a full understanding of confinement physics rather than the achievement of high parameters. Good progress is being made and we hope that increased understanding will show how we can improve the confinement performance of tokamaks by methods other than simply by making them larger.

12. Summary

1) JET has now been operating for four years. It has reached its design values for basic parameters such as discharge current and toroidal magnetic field strength.

2) Ion temperatures of 12-14keV have been reached when operating at low density with neutral beam heating.

3) The machine has shown the flexibility to be operated with

a magnetic separatrix which was not part of the original design. Operating in this way the transition to the H-mode regime of improved confinement has been demonstrated.

4) Plasma conditions have been reached which correspond to $Q \sim 0.1$ in the plasma core for a D-T plasma. ($Q = \frac{\text{Thermonuclear Power}}{\text{Power Input}}$)

5) Further increases in plasma current and heating power should permit the achievement of conditions close to 'scientific breakeven', ie $Q \sim 1$.

6) Extrapolating from the present JET data implies that a machine such as the 'enhanced NET' with a plasma current of 15MA should ignite.

7) The physics of plasma confinement in tokamaks is still a fascinating, rich and unresolved problem.

13. Acknowledgements

The experimental results quoted above are the result of long and hard work by the entire JET team under the leadership of Dr P-H Rebut.

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TABLE 1

JET PARAMETERS

MAJOR RADIUS (m)	3.0
MINOR RADIUS (m)	1.2
ELONGATION	≤1.8
TOROIDAL FIELD (T)	3.4
PLASMA CURRENT (MA)	
LIMITER BOUNDED	5.0 (7.0)
SINGLE NULL X-POINT	3.0 (4.0)
NEUTRAL BEAM POWER (MW	10 (20)
ICRH POWER (MW)	8 (20)

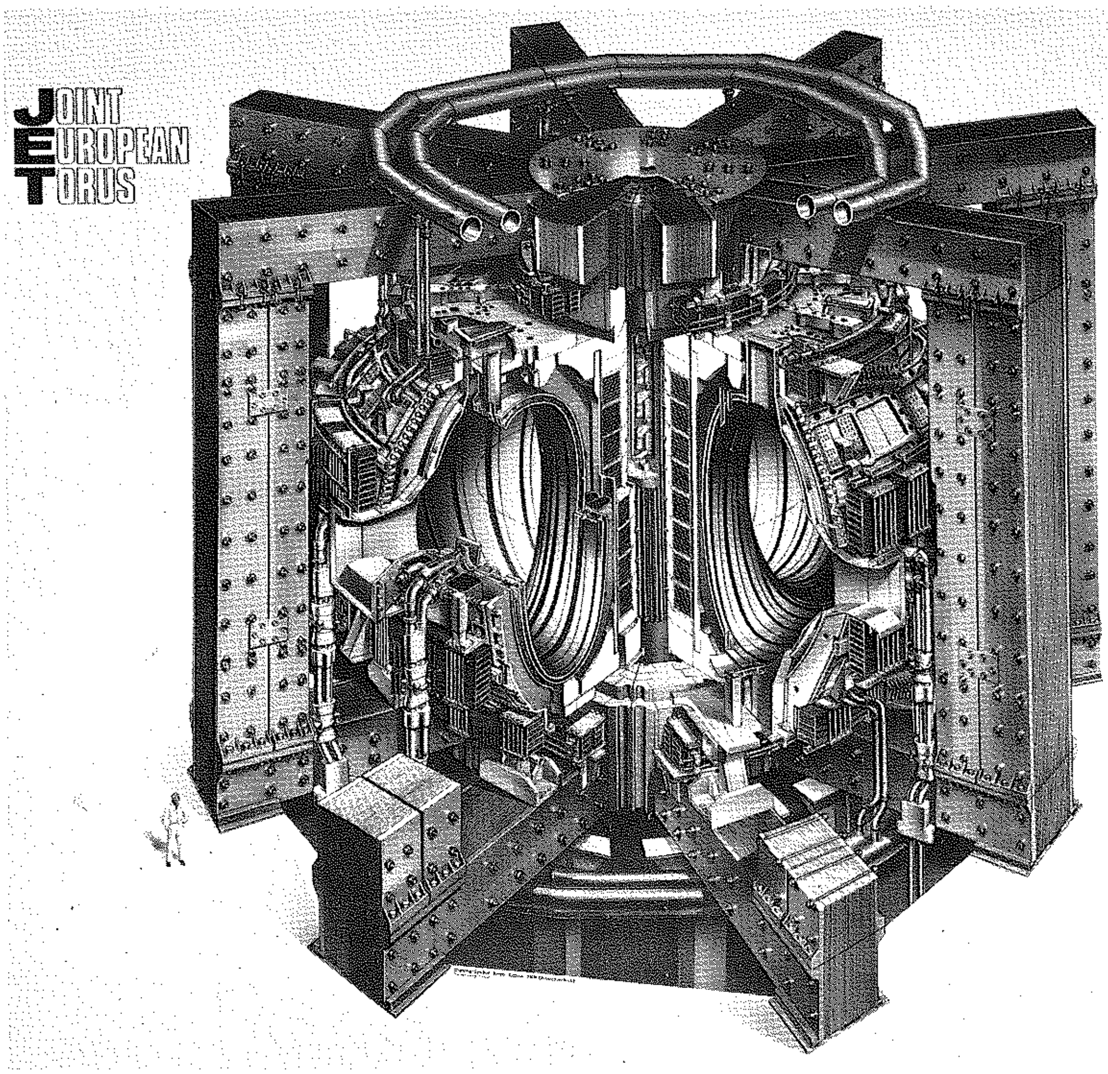

Fig. 1 Artist's impression of JET. Notable are the toroidal vacuum vessel with D-shaped cross-section, the eight iron transformer limbs, the central primary winding and the toroidal field coils.

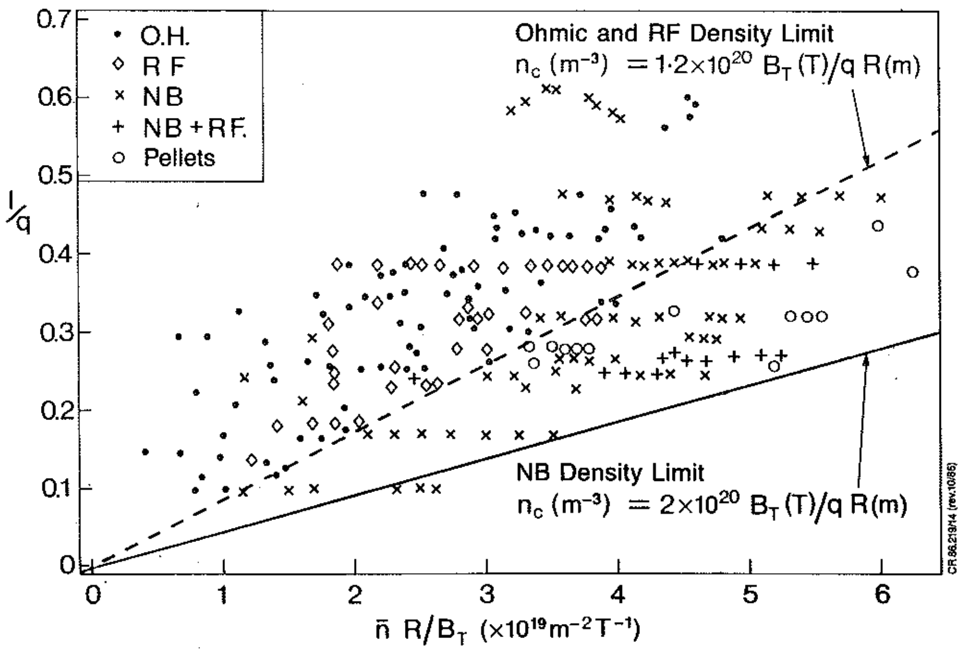

Fig. 2 The JET operating diagram in the $\frac{1}{q}$ versus $\frac{nR}{B}$ space. Points correspond to flat-top parameters of non-disruptive discharges. Lines show high density disruption limits.

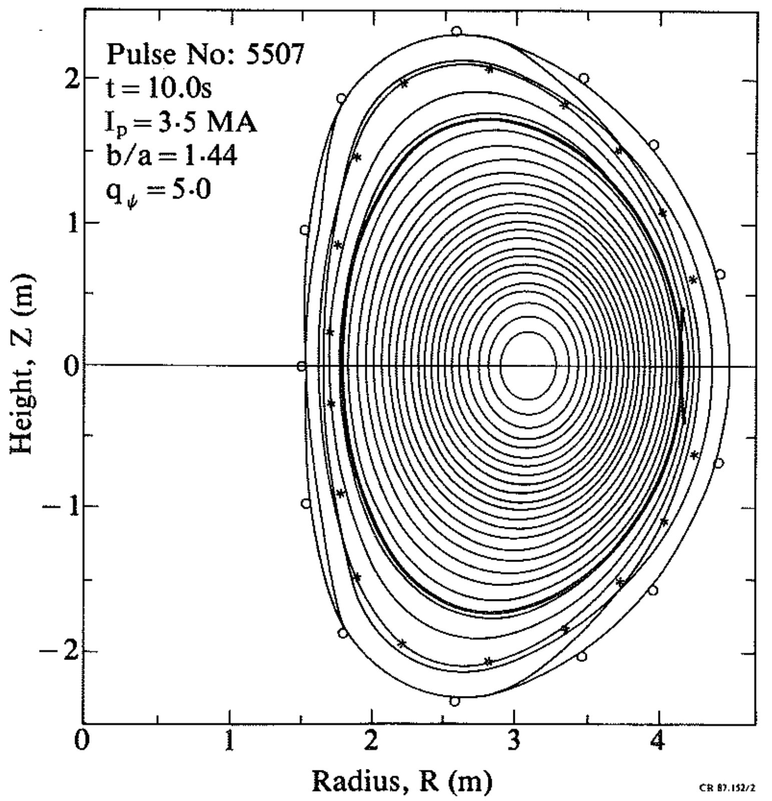

Fig. 3 Flux contours in the meridional plane. Contours show magnetic surfaces deduced from external measurements of fields and fluxes. In this case the plasma is bounded by the intersection of an outer magnetic surface with a material limiter on the equatorial mid-plane.

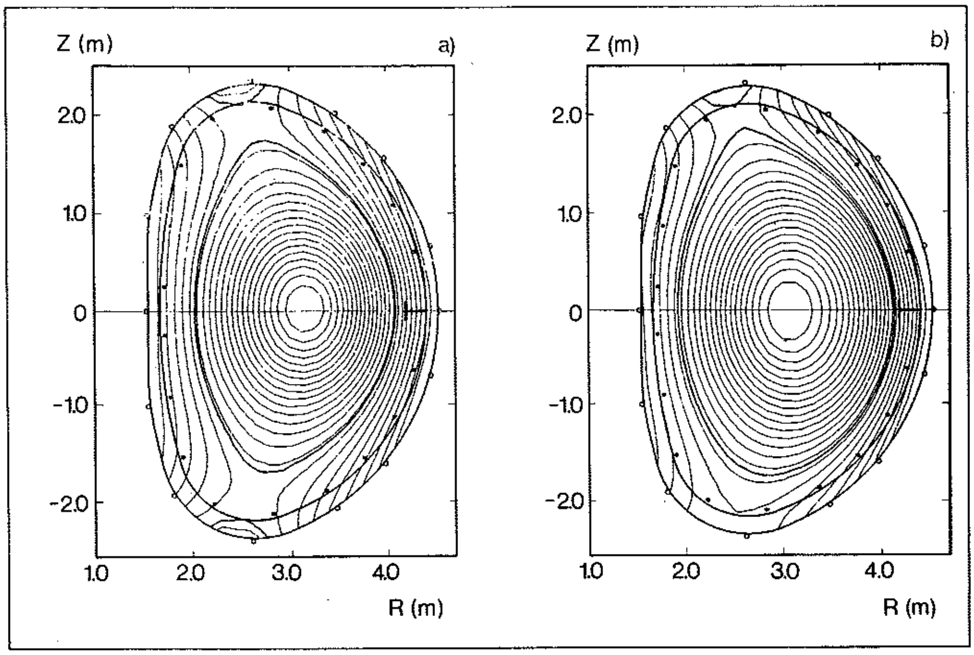

Fig. 4 Flux contours for two cases of separatrix-bounded plasmas. Double-null with X-points above and below the plasma, single null with one X-point above the plasma.

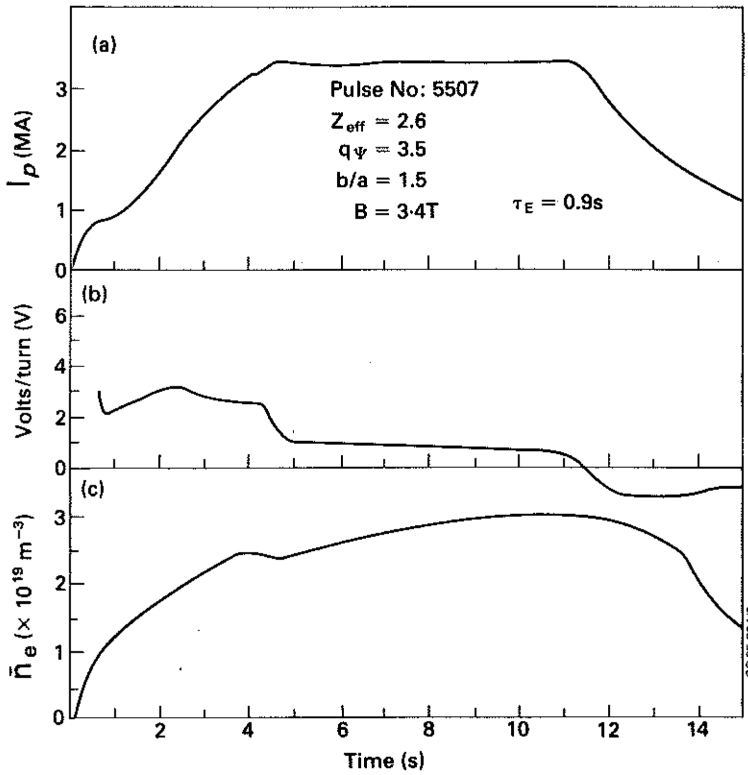

Fig. 5 Traces showing plasma current, driving (single turn) voltage and plasma density versus time.

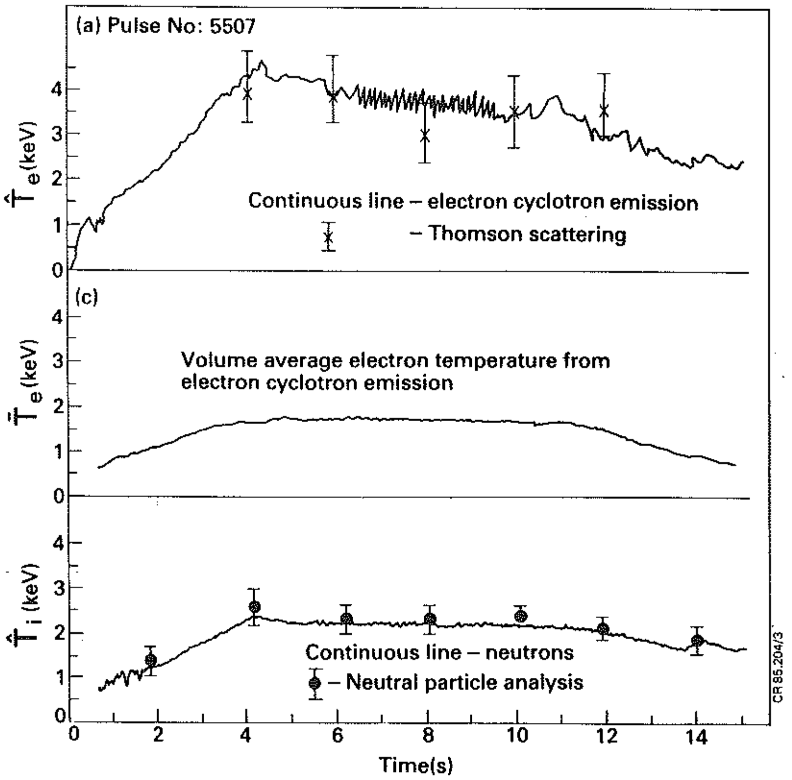

Fig. 6 Measured values of central electron temperature T_e, average electron temperature $\bar{T}_e$, and central ion temperature T_i for the same pulse as Fig. 5.

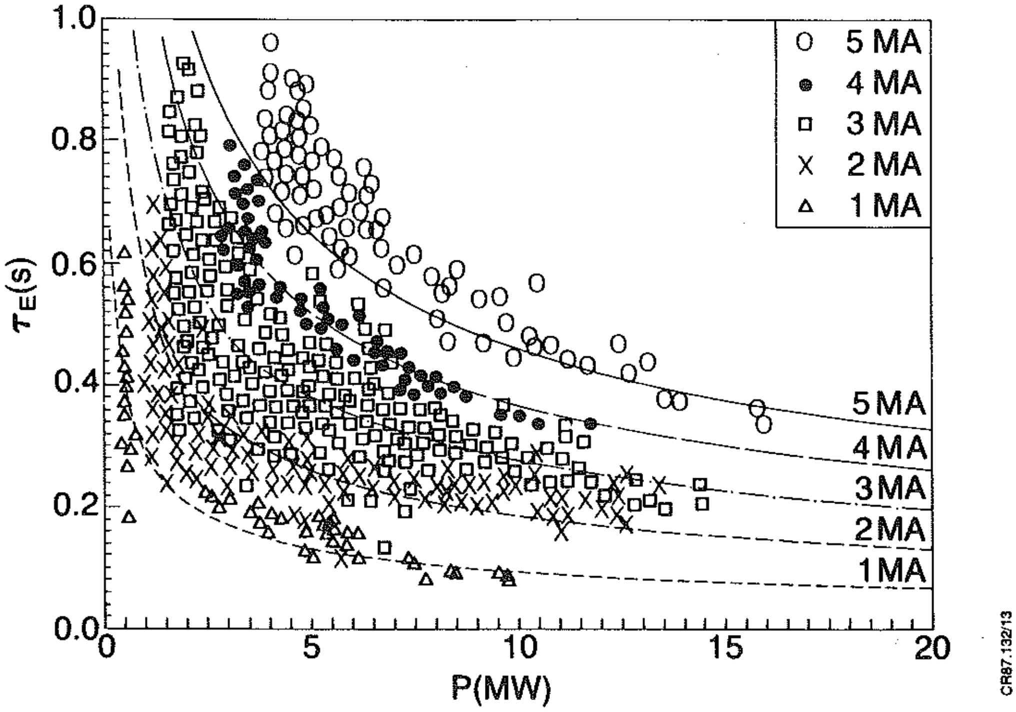

Fig. 7 Global confinement time τ_s versus input power for currents of 1, 2, 3, 4 & 5MA. All discharges bounded by limiter or inner wall. Lines show predictions of Goldston L-mode scaling.

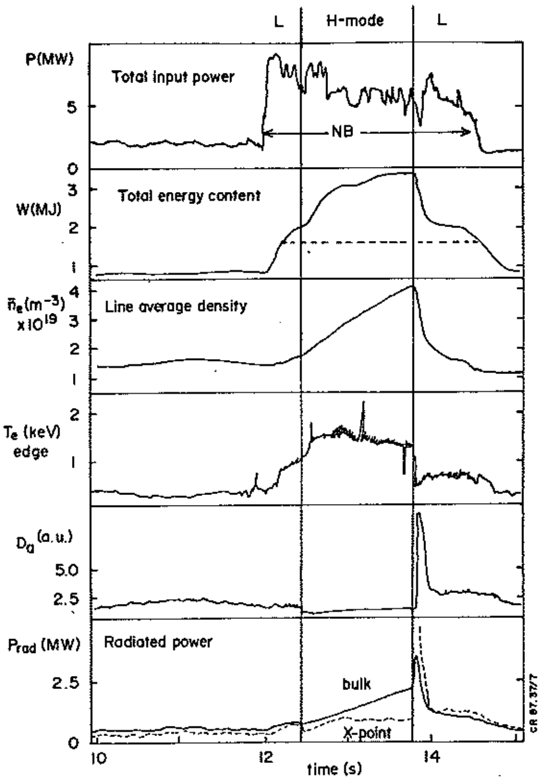

Fig. 8 Plasma parameters for a separatrix bounded (single null) plasma in which a transition to *H*-mode is made with neutral beam heating.

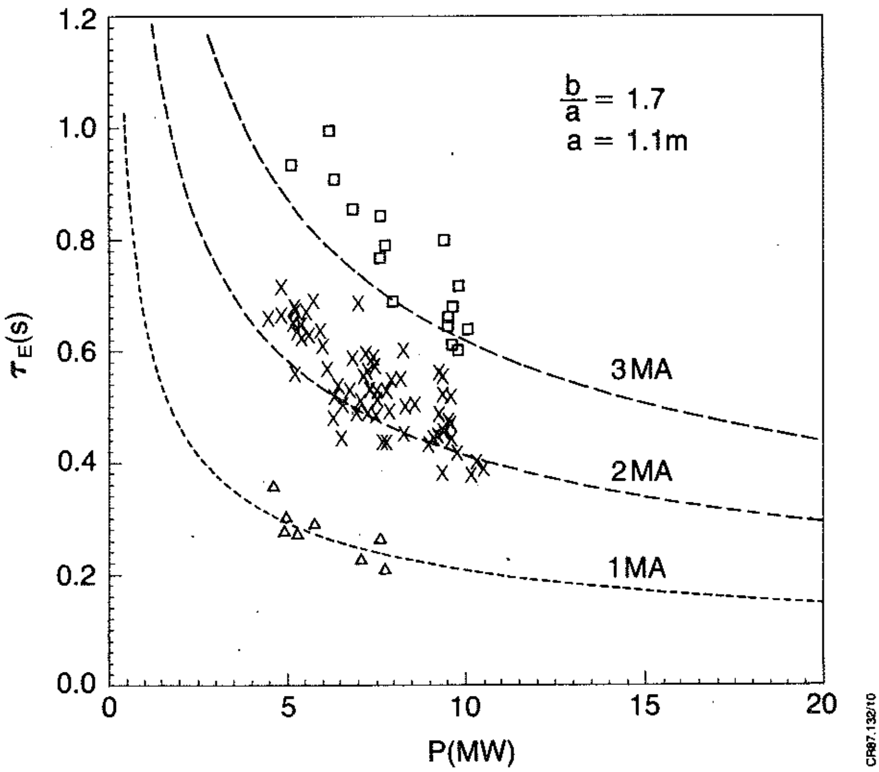

Fig. 9 Global energy confinement time (τ_ϵ) versus power input for *H*-mode discharges. Lines show Goldston *L*-mode scaling with τ_ϵ increased by a factor 2.

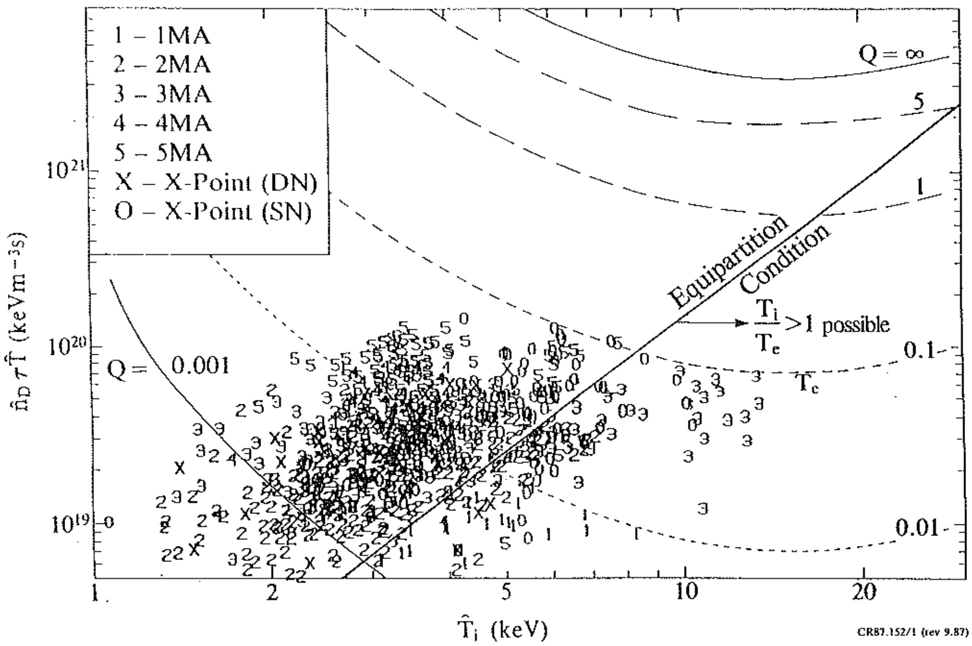

Fig. 10 Contours of constant Q in the $n_D\tau_\epsilon T_i$ versus T_i plane. Values are calculated for the plasma core, radius 0.3 m. Experimental points are marked by numbers denoting the plasma current level. Points with zero symbol (0) are for separatrix bounded plasmas with currents of 1 or 2MA.

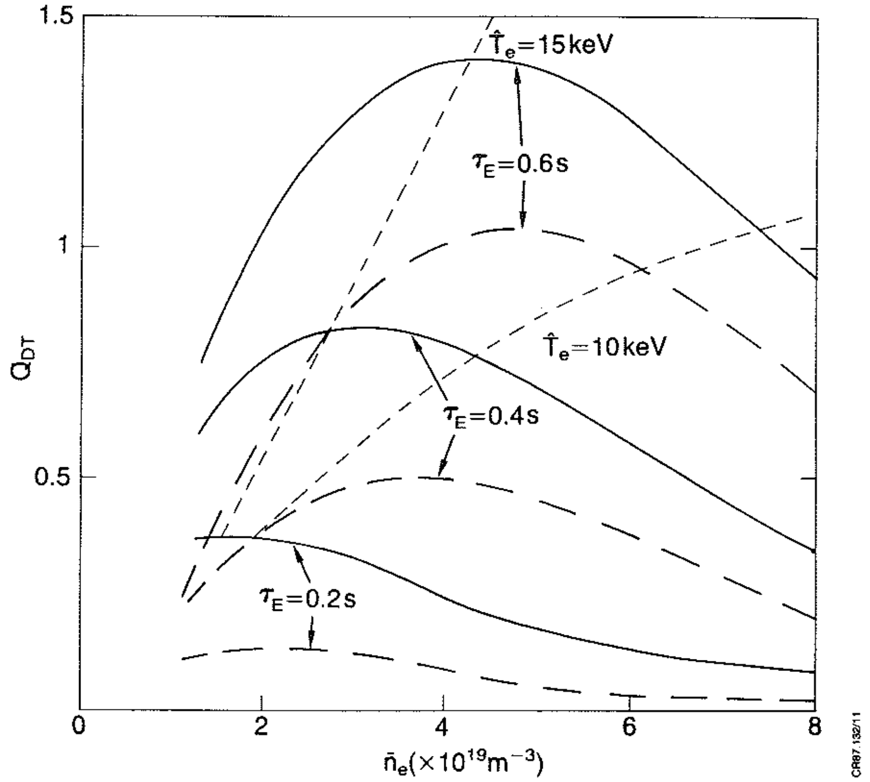

Fig. 11 Predicted Q values versus average density for two values of the global energy confinement time. Q values here are calculated for the whole plasma volume but assume no depletion (i.e. no impurities). Q_{th} is the thermonuclear contribution to Q_{TOTAL}. The difference is due to the contribution from beam plasma reactions.