Plasma Physics and Controlled Fusion

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To cite this article: A Ainsworth 1986 *Plasma Phys. Control. Fusion* **28** 1943

Plasma Physics and Controlled Fusion, Vol. 28, No. 12B, pp. 1943–1954, 1986
Printed in Great Britain

0741–3335/86 $3.00 + .00
IOP Publishing Ltd and Pergamon Journals Ltd.

CONFINEMENT & HEATING OF PLASMAS IN THE JET TOKAMAK

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ABSTRACT

The JET Tokamak has now been operated in a wide variety of conditions. These include,

1) plasma currents up to 5MA
2) plasmas bounded by limiters on the outer equatorial plane
3) plasmas bounded by the wall on the small major radius side of the torus
4) plasmas bounded by a magnetic separatrix
5) additional heating at the ion cyclotron frequency, up to 6MW
6) additional heating by ~ 70keV neutral beams (H or D) at up to 7MW
7) combined heating with both techniques

The results from these various modes of operation are described. These include ion temperatures up to 10keV and D-D neutron rates up to 2×10^{15}/sec.

The results highlight the problem of confinement degradation. Several measures are planned to reduce or overcome this effect, however, even with confinement degradation it should be possible to reach conditions in which the thermonuclear output is equal to the power input (Q=1). This will require that the average plasma density is kept low (eg 2-3 $10^{19}m^{-3}$). This should be possible due to the remarkable pumping action of carbon walls found in JET.

INTRODUCTION

The aims of the JET project remain those set out at the start of the design phase in 1974, namely to study,

1) the scaling of plasma behaviour as plasma parameters approach the thermonuclear reactor regime,
2) plasma-wall interactions in these conditions,
3) plasma heating,
4) α-particle production, confinement and consequential plasma heating.

Item (4) requires that the machine operates eventually in a deuterium-tritium mixture. The machine has therefore been designed for remote maintenance and tritium compatibility. The design and construction of the machine has been described by Huguet (1984). Recent physics results on heating and impurity behaviour have been presented by Lallia (1986), Düsing (1986) and Engelhardt (1986).

Table 1

Parameter	Design Values	Operational Values
Plasma minor radius (horizontal)	1.25m	0.8 - 1.2m
Plasma minor radius (Vertical)	2.10m	0.8 - 2.1m
Plasma major radius (R_o)	2.96	2.5 - 3.4m
Toroidal Magnetic field at $R = R_o$	≤ 3.45T	≤ 3.45T
Plasma Current	≤ 4.8MA	≤ 5.0MA

Table 1 shows that design values of the key JET parameters. As can be seen these design values are now routinely used or exceeded in present operations. Tokamak discharges are run with the vacuum vessel at 300°C. Three different modes of operation have been used,

1) plasma bounded by eight carbon limiters on the outer equatorial plane (Figure 1),
2) plasma bounded by carbon tiles on the inner equatorial plane (small major radius side of vacuum vessel),
3) plasma bounded by magnetic separatrix with X-points at the top and bottom of the torus (Figure 2).

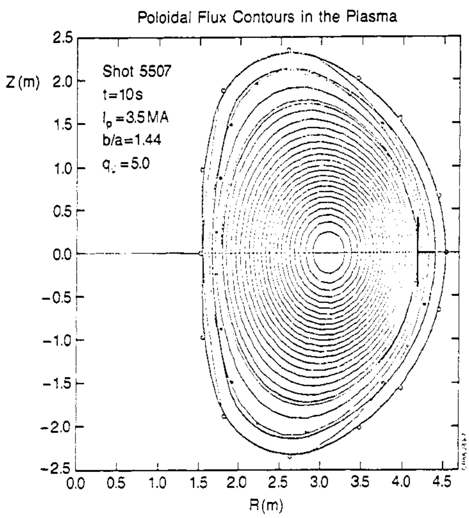

Fig. 1 Poloidal flux contours for a representative discharge bounded by the outer limiters.

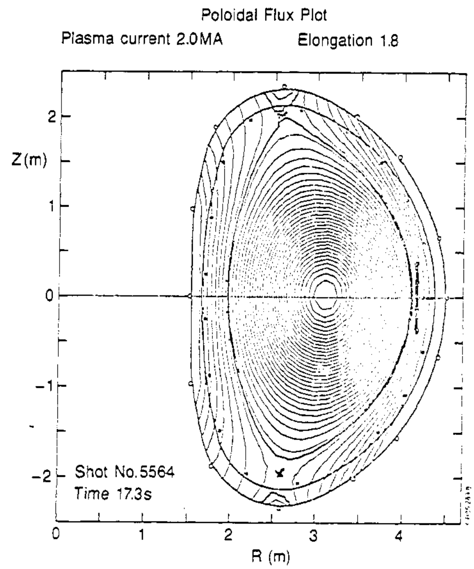

Fig. 2 Poloidal flux contours for a representative discharge bounded by a magnetic separatrix with X-points at the top and bottom of the plasma cross-section. (Double-null configuration).

PLASMA HEATING

Two techniques have been used to heat the plasma in addition to the inescapable ohmic heating that results from the passage of current through the plasma. In the first technique radio frequency power (25-55MHz) is coupled through loop antennae to fast waves propagating inwards from the low field side of the plasma. These waves are absorbed at the resonance layer for minority ions in the plasma, ie where $\omega_{RF} = \frac{Ze\,B_t}{M_i c}$ where Z is the charge, M_i the mass of these minority ions and B_t the toroidal field strength. Both H and He^3 minorities have been used in JET deuterium plasmas with concentrations relative to the bulk ions of a few percent. The minority ions are heated to high equivalent temperatures (~30-60keV) and transfer their energy to bulk ions and electrons by normal (Coulomb) collision processes. During the experimental campaign reported here up to 6MW of RF power was injected into the torus from 3 loop antennae. Pulses were several seconds in duration.

The second technique is that of neutral beam injection. Powerful ion beams are extracted and accelerated from multi-aperture ion sources. The ion beams are neutralised by passage through gas cells to give beams of neutral atoms. These cross the confining magnetic fields unaffected and enter the plasma where they are ionised by collisions with ions and electrons. The resulting trapped fast ions (energies 30-80keV) then transfer their energy to the bulk plasma by collisional processes. Thus there is a basic similarity between the two technique as used on JET. Minority species ion cyclotron heating being equivalent to internal neutral injection. During the campaign reported here 8 ion sources have been used to inject up to 8MW of deuterium beams at voltages of about 75kV. About 76% of the power injected consists of neutral atoms with the full energy ie 75keV, the remaining power is carried by atoms with 1/2 and 1/3 of this energy.

OPERATING DIAGRAM

Figure 3 shows the JET operation in normalised current and density space for the three cases, ohmic heating only, ohmic plus radio frequency heating, and ohmic plus neutral beam heating.

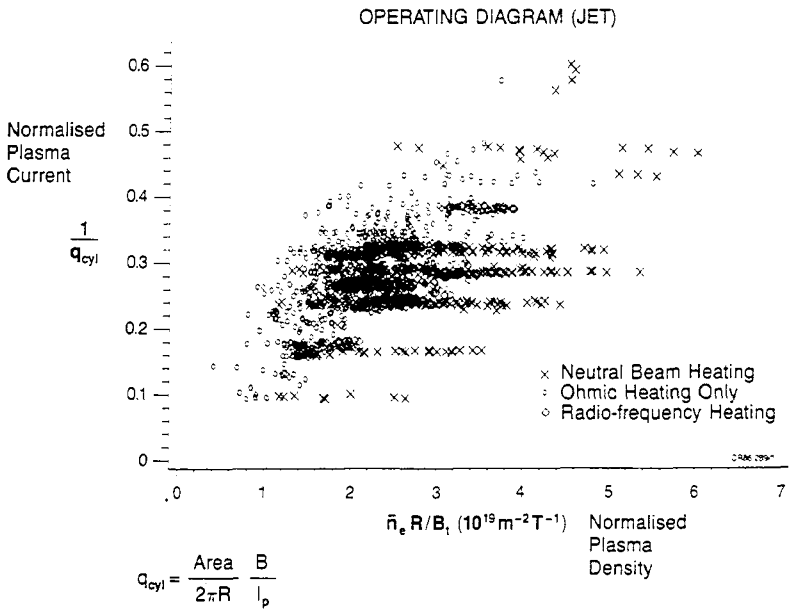

Fig.3 Operating diagram for JET in the normalised current ($1/q_{CYL}$) versus normalised density ($\bar{n}\ RB_t$) plane.

The current is normalised as

$$\frac{1}{q_{CYL}} = \left(\frac{2\pi R}{\text{Area}\ B_t}\right) \times I_p$$

and the density as $\bar{n}_e \frac{R}{B_t}$. Here the area is the cross-sectional area of the plasma and q_{CYL} is the tokamak safety factor defined for an equivalent circular cross-section plasma (the safety factor is the number of times a field line encircles the major axis in going once around the minor axis). R is the major radius of the plasma, I_p the plasma current (CGS units).

For a given normalised current ($1/q_{CYL}$) there is a band of operating densities. Below a certain limit the discharge fails to break down, above a critical density the discharge is suddenly terminated by a disruptive instability, the plasma current falling uncontrollably to zero in a few tens of milliseconds. From Figure 3 it can be seen that the addition of radio frequency power does not significantly increase the density limit above the ohmic value. By contrast neutral beam heating at a similar power level permits up to an 80% increase in density. From this evidence it would seem that power alone does not increase the limit but the combination of power and internal fuelling corresponding to injected particle beams does increase the limiting density. An important point related to this diagram is the question of terminating a neutral beam heated discharge without having a disruption. If the beams are simply switched off with the density above the critical value for ohmic heating alone then a disruption can be confidently predicted. A remarkable feature is that if the discharge is moved to the inner wall ($20m^2$ carbon tiles) before the beams are turned off then the unexpectedly strong pumping action of the inner wall can be used to reduce the density below the ohmic limit and so permitting beam switch-off without disruption. This is extremely important for safe repetitive machine operation although the physical and possibly chemical processes involved in this pumping action are not understood.

PULSE PROPERTIES

Figures 4 & 5 show the time history of several key parameters during a typical pulse. The discharge is first established ohmically on the outer limiters and the current is ramped up

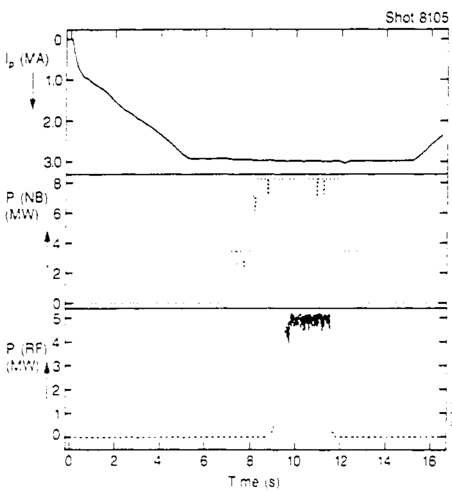

Fig.4 Time traces of plasma current, neutral beam power and radiofrequency power for shot 8105.

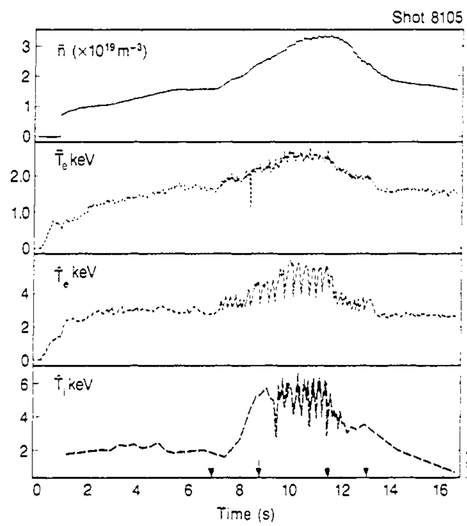

Fig.5 Time traces of line-average electron density $\bar{n}$ volume average electron temperature $\bar{T}_e$ peak electron and ion temperature $\hat{T}_e$, $\hat{T}_i$ for shot 8105. Arrows on timebase show successively the switch-on of neutral beams switch-on of RF, switch-off of RF and switch-off of beams.

to the flat-top value of 3.0MA. With the pulse established the neutral beams are turned on at 7 & 8s into the pulse. At about 9s an additional 5MW of RF is injected. At 12 seconds the plasma is moved to the inner wall and the density which had been rising due to beam fuelling starts to fall. Between 11 & 14s the additional heating power is progressively reduced to zero without a plasma disruption. The density rises by ~2 during heating, the central ion temperature more than doubles while the increases in both central $(\hat{T}_e)$ and volume average $(\bar{T}_e)$ electron temperatures are much more modest. The principal effect of the RF heating in this pulse is to increase the sawtooth amplitude on both electron and ion temperatures in the centre.

ENERGY CONFINEMENT

The energy confinement time τ_E is defined as,

$$\tau_E = \frac{W}{P - dW/dt} \qquad (2)$$

where W is the total energy content in the plasma and P the total power input. For most JET data near steady-state conditions are reached so that $dW/dt \ll P$.

In Figure 6 the confinement time for ohmic heating only discharges is plotted against the scaling factor $\bar{n}qR^2a$. Early JET results showed τ_E to be linearly proportional to this factor as did the experiments in earlier and smaller tokamaks (Goldston 198-). More recent JET results (Bickerton 1985) show that τ_E eventually saturates as $\bar{n}$ is increased, also a common observation on other tokamaks. The data in Figure 6 is divided into points corresponding to plasmas bounded on the outer limiter and others with double null x-point operation. It is evident that these latter are all on the high side showing a mean improvement of the order 10-20%.

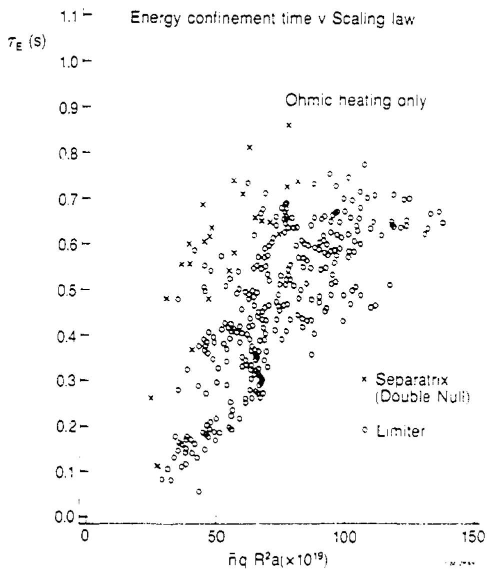

Fig.6 Energy confinement times for ohmic discharges plotted against the scaling combination $\bar{n}\ q\ R^2\ a$. Double null and outer limiter data are differentiated.

Figure 7 shows the energy content of the plasma against the total power input. The highest power level is achieved with combined ohmic, neutral beam and RF heating. The results do not depend significantly on plasma density. At high powers they follow closely the values predicted by the L-mode scaling (Goldston 1984), that is $W = P_{TOTAL} \cdot \tau_\varepsilon$ where

$$\tau_\varepsilon = 3.7\times10^{-2}\ I_p\ P^{-1/2}\ R^{1.75}\ a^{-0.37}\ K^{1/2} \text{ seconds} \tag{3}$$

where the units are MA, MW, m and K is the plasma elongation. This form derived on the basis of results in much smaller machines predicts with surprising accuracy the JET performance at 1-5MA provided that the additional heating power is several times the ohmic contribution.

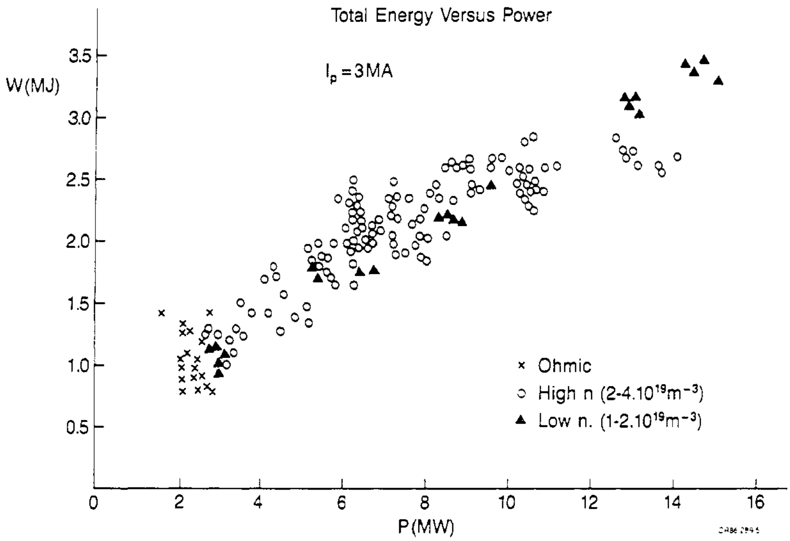

Fig. 7 Plasma energy content versus input power for the full range of operation with and without additional heating at 3MA. High and low density ranges are differentiated showing that the density dependence is weak.

The degradation of confinement time with power described in (3) is seen equally with neutral beam or RF heating separately or combined. This result is of basic importance since it gives a severe limitation to the JET performance when extrapolated to the power and current levels presently planned for the later stages of the experiment.

THERMONUCLEAR REACTIONS

The thermonuclear fusion power in a D-T mixture due to nuclear reactions between thermal ions has the dependence

$$P_{TN} \propto n_i^2\ (\overline{\sigma v})\ Y$$

where P_{TN} is the power per unit volume, n_i the ion density, $(\overline{\sigma v})$ the fusion cross-section ion velocity product averaged over the distribution function and Y the energy yield per reaction.

The product $\overline{\sigma v}$ depends on the ion temperature,

$$\overline{\sigma v} \propto T_i^{\gamma}$$

where γ is an index which reduces progressively with rising ion temperature to ~2 in the themonuclear range of interest, ie 7keV < T_i < 20keV. Since the local energy density nT is proportional to $P\tau_\varepsilon$ where P is the input power, the important ratio Q_{TN} between the thermonuclear output and the power input has the dependence

$$Q_{TN} = \frac{P_{TN}}{P} \propto n^{(2-\gamma)}\, P^{(\gamma-1)}\, \tau_\varepsilon^{\gamma}$$

In the neighbourhood of $\hat{T}_i$ ~ 5keV, which is the case for JET results reported here, γ = 3, so that

$$Q_{TN} \propto n^{-1}\, P^2\, \tau_\varepsilon^3$$

Using the L-mode scaling discussed earlier in which $\tau_E \propto P^{-½}$ we find

$$Q_{TN} \propto P^{½}\, n^{-1}$$

In this regime there is a clear advantage in increasing the input power despite the resulting degradation in confinement time. This takes no account of the hot-ion mode in which with suitable heating technique (eg JET neutral beams) the input power is first given to the ions so that $T_i > T_e$. Inclusion of this effect still further increases the advantage of operation at low density.

With central ion temperatures ~15keV then γ = 2 and $Q_{TN} \propto P\tau_\varepsilon \propto P^0$ with L-mode scaling. Thus once the ion temperatures reach this range there is no gain in Q_{TN} with further increases in heating power.

BEAM-PLASMA REACTIONS

The trapped fast deuterons injected at 70-80keV by the neutral beam system slow down on the background ions and electrons and have a significant chance of undergoing fusion reactions. The beam-plasma contribution (P_{b-p}) to the fusion power has the dependence,

$$P_{b-p} \propto n_b\, n\, \langle \overline{\sigma v} \rangle_{\varepsilon b}\, Y$$

where n_b is the density of fast deuterium ions, n the density of bulk tritium ions, $\langle \overline{\sigma v} \rangle_{\varepsilon b}$ the fusion cross-section velocity product averaged over the fast ion distribution and Y the energy yield per reaction. For a case with only neutral beam heating the fast ion density n_b is

$$n_b \propto \frac{P\,\tau_s}{\varepsilon_b}$$

where τ_s is the slowing down time for fast ions. Under present JET conditions with relatively low volume average electron temperatures (2-3keV) the initial slowing down is predominantly on the electrons so that

$$\tau_s \propto \frac{T_e^{3/2}}{n}$$

leading to the ratio of beam plasma fusion power to the input of the form

$$Q_{b-p} \propto \frac{P^{3/2}\ \tau_\varepsilon^{3/2}}{n^{3/2}}$$

or for the L-mode scaling,

$$Q_{b-p} \propto \frac{P^{3/4}}{n^{3/2}}$$

So once again for present JET parameters we find advantage in operating at the highest neutral beam power and the lowest plasma density.

OVERALL FUSION POWER

The total fusion yield will then be the sum

$$Q_{TOTAL} = Q_{b-p} + Q_{TN}$$

With present JET parameters the dominant contribution is Q_{b-p}. Scaling from the present maximum D-D neutron yields of ~ 3×10^{15} n/s gives Q_{TOTAL} ~ 10^{-1}. This is the value that would be achieved by operation at present levels in a 50/50 D-T mixture rather than the present 100% D.

From these considerations it is evident that the performance of JET will be increased over the present level by maximising the neutral beam power input and minimising the density. This optimum path is determined by the L-mode confinement scaling.

Representative values for the present JET operation are shown in Table 2.

Table 2

	Ohmic	RF	Neutral Beam	RF + Neutral Beam
P(MW)	3.5	6.3	7.6	14.2
$\hat{T}_i$ (keV)	2.9	3.6	10.0	5.4
$\hat{T}_e$ (keV)	3.8	4.2	5.5	4.8
$\bar{n}(10^{19}m^{-3})$	3.5	3.5	1.6	3.4
τ_E (s)	0.65	0.4	0.29	0.23
Q_{TN}	5×10^{-3}	5×10^{-3}	5×10^{-2}	10^{-2}
Q_{DD} (measured)	1.8×10^{-5}	2.3×10^{-5}	2.5×10^{-4}	1.4×10^{-4}
Equivalent Q_{D-T}	5×10^{-3}	5×10^{-3}	1.0×10^{-1}	7×10^{-2}

The line Q_{TN} gives the calculated thermonuclear Q for equivalent plasma conditions in a 50:50 deuterium-tritium mixture. Q_{DD} gives the measured ratio of thermonuclear output in the deuterium plasma used in present experiments. This is simply based on 7.3MeV of energy released per detected neutron together with the measured neutron yield. The equivalent Q_{D-T} is based on scaling from Q_{DD} taking into account the increased cross-sections for deuterium-tritium fusion reactions relative to those for deuterium-deuterium. Experimentally the highest value of Q_{DD} is obtained for low density and neutral beam only and is dominated by the beam-plasma contribution.

PERFORMANCE PROSPECTS

With the developments already in hand we expect that JET will eventually be capable of operating at 7MA with a limiter-bounded plasma or 4MA with a separatrix-defined boundary. For the separatrix case we may expect the so-called H-mode leading to a two-fold improvement in confinement (Goldston, 1984). In both cases the effective heating power into the plasma will be about 40MW. Then extrapolating we find the following performance predictions,

I_p = 7MA Limiter, L-mode confinement

$\tau_\varepsilon \sim 0.34$s giving for D-T

$Q_{TN} \sim 0.25$, $Q_{b-p} \sim 0.6$, $Q_{TOTAL} \sim 0.85$, $P_\alpha \sim 6$MW (P_α = α-particle power)

I_p = 4MA, Separatrix, 2 x L-mode confinement

$\tau_\varepsilon = 0.4$s

$Q_{TN} \sim 0.4$, $Q_{b-p} \sim 0.6$, $Q_{TOTAL} \sim 1.0$, $P_\alpha \sim 8$MW.

Thus in both cases $Q_{TOTAL} \sim 1$ and "scientific breakdown" is achieved. To improve on this and to achieve $Q_{TN} \sim 1.0$ will require some improvement in the confinement scaling and/or in the radial profiles. Measures designed to effect such improvements are in hand. They are all in the research class and will require several years to be implemented and fully tested.

SUMMARY

a) With ohmic heating alone record energy confinement times up to 0.8s have been reached. Ion and electron temperatures are 3-5keV.
b) With additional heating the confinement time is rapidly degraded independently of the heating method.
c) Central ion temperatures up to 10keV are reached at low density with neutral beam heating.
d) Conditions equivalent to a $Q_{TOTAL} \sim 0.1$ in D-T have been reached.
e) With the presently observed scaling further progress requires operation at low density and maximum heating power.
f) To achieve truly thermonuclear Q values of unity or more requires breaking out of the present scaling. Measures to do this are in hand but they are of a speculative research nature and will require time for full exploitation.

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