Resistively Heated Plasmas in JET: Characteristics and Implications

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Resistively heated plasmas in JET: characteristics and implications

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The behaviour of ohmically heated plasmas in JET is described and evaluated. On the basis of this evaluation and taking into account various other developments in the tokamak field, an assessment is made of the prospects for fusion research with the JET device.

1. Introduction

The objectives of research with JET remain as they were formulated at the inception of the project in 1974. They are listed below.

(*a*) To study the way the confinement and plasma properties scale as the dimensions and parameters approach those necessary for a reactor.

(*b*) To examine and control the plasma–wall interaction and impurity influx in these conditions.

(*c*) To demonstrate effective heating techniques capable of producing high temperature in JET in the presence of the prevailing loss processes.

(*d*) To study α-particle production, confinement and subsequent plasma interaction and heating: the physics of a reacting plasma.

The experimental programme began in June 1983, with plasmas created and heated by the ohmic effect of current driven through the plasma by transformer action. This current, in the tokamak configuration, also provides the magnetic field that confines the plasma, isolating and insulating it from the surrounding walls of the toroidal vacuum vessel. By using these ohmic plasmas, effective impurity control has been developed, in pursuance of (*b*) and extensive investigations have been made of the confinement properties according to (*a*). The first studies of plasma heating with non-ohmic methods have begun and are described in other papers in this symposium. The studies necessary to meet (*d*) remain the main aim of the project. The programme for the next few years is designed to establish the plasma conditions required for these studies.

The present paper will describe the results obtained with ohmically heated plasmas. It will examine the implications of these results on the prospects of obtaining plasma conditions in JET necessary to study a reacting plasma.

2. Results

The development of JET as an electromagnetic device is illustrated in figure 1. It shows that with increasing operating experience the plasma current was increased from an initial level of 70 kA for 0.1 s to almost 5 MA in a pulse with total duration greater than 16 s. The design value of 4.8 MA has thus been surpassed. Figure 2 shows the characteristics of a discharge in which the plasma current is maintained at 5.1 MA for more than 3 s. There is some control

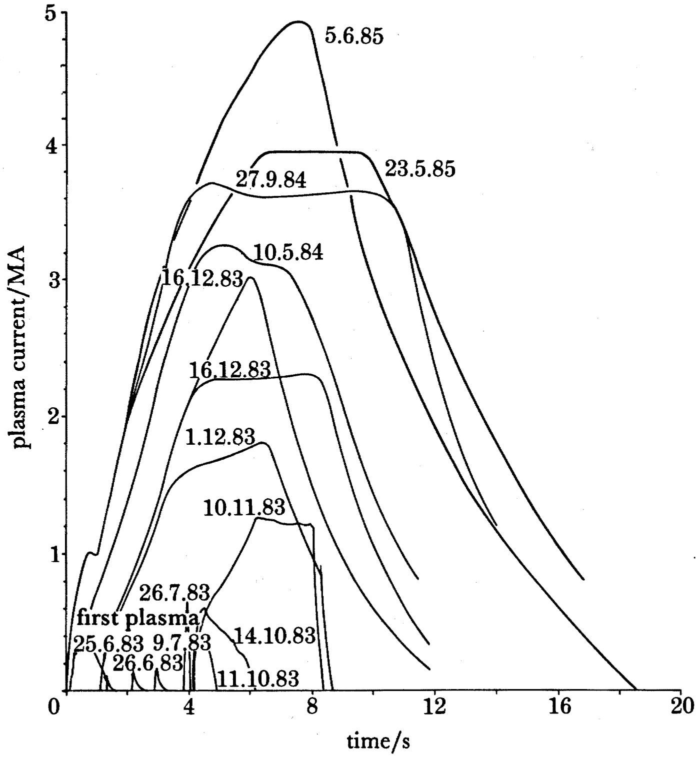


FIGURE 1. Progress with the plasma current in JET, June 1983 to June 1985.

of plasma density during the pulse by controlled puffing of deuterium at the wall but, as may be surmised from the similarity of the density and current traces, much of the fuelling is by deuterium gas reemitted by the walls in a recycling process.

The magnetic flux surfaces in the plasma can be deduced from magnetic measurements and equilibrium theory and are shown in figure 3 for the discharge in figure 2.

Measurements similar to these have now been made for a wide range of ohmic discharges in JET. Table 1 summarizes the range of parameters that has been measured.

3. DENSITY AND CONFINEMENT-TIME BEHAVIOUR

Figure 4 summarizes experiments carried out to obtain the highest density in ohmic discharges. The form of plot chosen shows there is a limit of $\bar{n}Rq_{\mathrm{cy}}/B_{\mathrm{T}} = 12 \times 10^{19}\ \mathrm{m^{-2}\ T^{-1}}$ (measured in steady-state conditions at the end of the current flat top), which is not exceeded in these ohmic discharges. This limit is reached only for the discharges that have the lowest values of Z_{eff}.

The quantity q_{cy} expresses the ratio of poloidal and toroidal fields and is defined as $q_{\mathrm{cy}} = 2\pi/\mu_0(aB_{\mathrm{T}}/I_{\mathrm{p}})\ (a/R)\ (b/a)$.

Figure 5 shows the variation of energy replacement time (τ_{E}) as the mean electron density is scanned over the available range with other set parameters held constant. The dashed line is the value given by Goldston's (1984) fit to data from smaller tokamaks (the parameters used correspond to all the points plotted, except for the small plasmas ($a = 0.8$ m)). At lower densities the JET data exceed the Goldston fit and τ_{E} increases linearly with mean density. However,

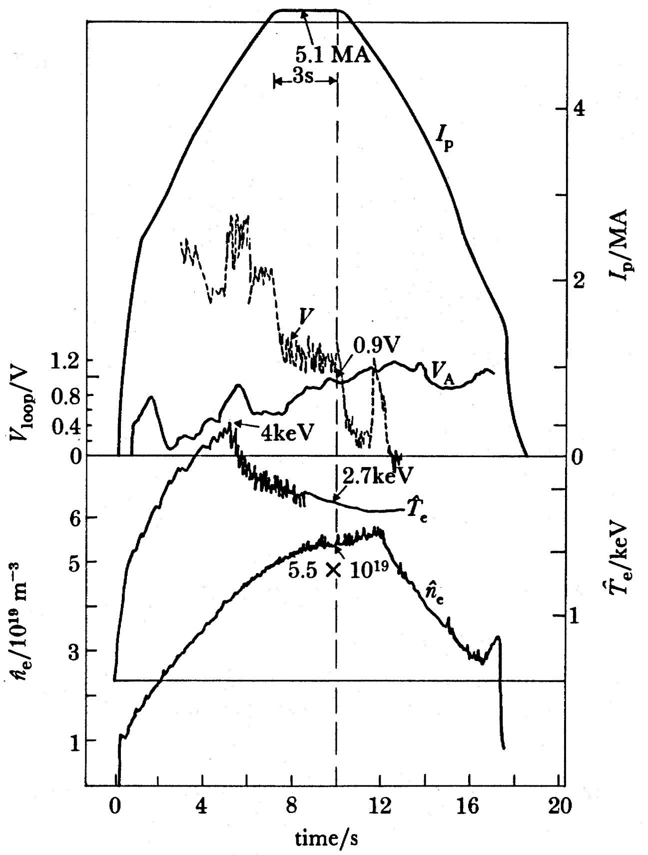


FIGURE 2. A typical JET pulse (no. 7293) in deuterium, with plasma current greater than 5 MA. Traces are shown that record the plasma current (I_p); the measured voltage around the plasma major axis at the vacuum vessel (V); the inferred loop voltage on the plasma minor axis (V_A); the electron temperature at the plasma axis (T_e) and the volume electron density at the plasma axis (n_e). The time resolution differs at different times on the digitally recorded traces. For this plasma on the current flat top the plasma elongation (b/a) is 1.4; the toroidal stabilizing field (B_T) is 3.4 T; the plasma kinetic energy content (W_p) is 3 MJ and the energy replacement time is 0.6 s. The magnetic configuration is characterized by the twist of the field lines (q_ψ), the number of transits the long way round the torus which a field line must make for one transit the short way. In this case, on the outer surface in contact with the limiter $q_\psi = 3.4$.

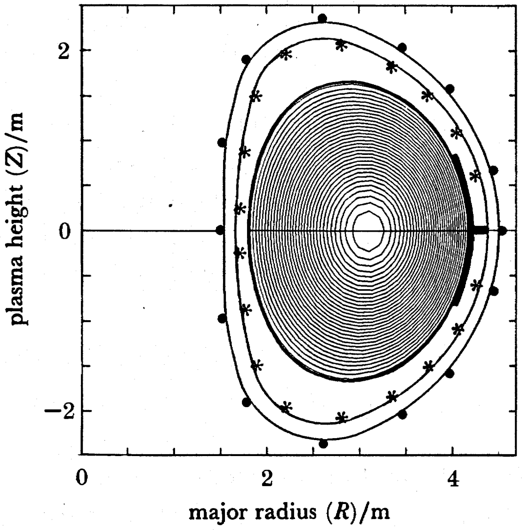


FIGURE 3. Magnetic surfaces in the plasma. No. 7293, time into pulse was 9 s, $I_p = 5.17$ MA, $b/a = 1.4$, $q_\psi = 3.3$; the location of the magnetic measurement coils and loops are indicated by $*$ and ●.

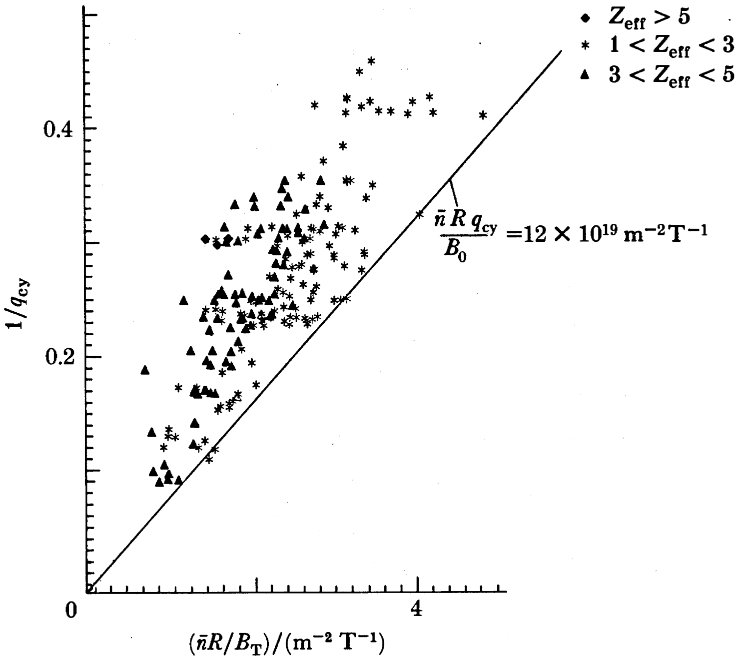


FIGURE 4. Diagram showing the limiting density obtained in ohmic discharges. q_{cy} is the ratio of toroidal to poloidal field as defined in the text, the other quantities are defined in table 1.

TABLE 1. PARAMETER RANGES FOR OHMIC DISCHARGES

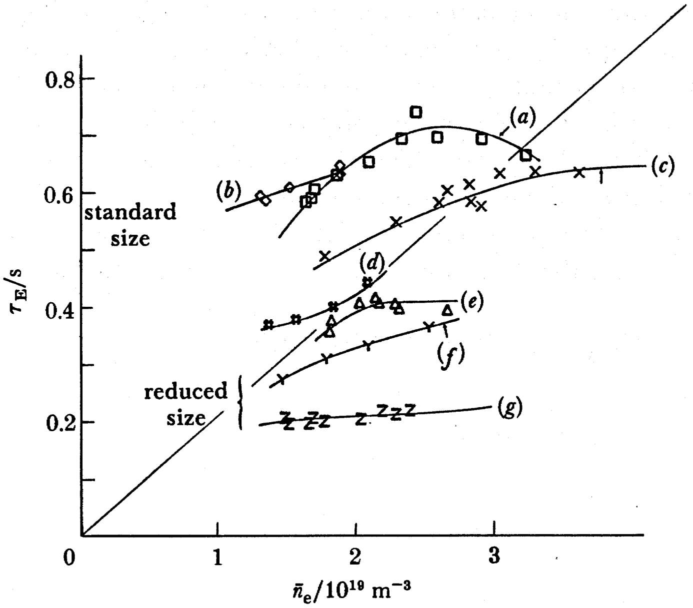
plasma current	I_p	$\leqslant 5$ MA
toroidal field	B_{T}	$\leqslant 3.4$ T
minor horizontal radius	a	0.8–1.2 m (typically 1.1 m)
major radius	R	2.5–3.4 m (typically 3.0 m)
field-line twist	q_ψ	3.2–∞
elongation ratio	b/a	1.02–1.65
loop voltage on axis	V_{A}	0.4–1.3 V (typically 0.7 V)
effective ion charge number	Z_{eff}	2.4–10 (typically 3)
ratio of plasma- to poloidal-magnetic-field pressure	$\beta_{I\,(\text{kin})}$	$\leqslant 0.3$
maximum steady-state electron temperature	T_{e}	1.5–6 keV
maximum steady-state ion temperature	T_{i}	1–3 keV
mean electron density	$\bar{n}_{\text{e}}$	$1\text{–}3.6 \times 10^{19}\ \text{m}^3$
plasma energy replacement time	τ_{E}	0.15–0.8 s
product of $n_{\text{D}}\,\tau_{\text{E}}\,T_{\text{i}}$ in core plasma	$n_{\text{D}}\,\tau_{\text{E}}\,T_{\text{i}}$	$0.6\ (\pm 0.2) \times 10^{20}\ \text{m}^{-3}$ s keV
neutron production rate	Γ_{N}(D–D)	$\leqslant 7 \times 10^{13}$ neutrons s^{-1} ($\approx 6 \times 10^{14}$ total)

at higher densities this increase tends to saturate. These data, supplemented by extensive data measured during 1985 are plotted as a power-law regression fit on the set parameters in figure 6. The estimated errors of measurement are indicated by the error bar shown. It will be seen that a tolerably good fit is obtained. However, such fits should be treated with caution especially in view of the rather clear saturation of τ_{E} with density shown in figure 5. The best fit, shown by the dashed line is:

$$\tau_{\text{E}} = 0.013 n^{0.38} B_{\text{T}}^{0.57} q_{\text{cy}}^{0.33} R^{3.2} (a/R)^{1.7}\, A^{0.56} (b/a)^{0.21}, \tag{1}$$

where A is the atomic mass (points are for H_2 and D_2 plasmas only), units are MKS with n in units of $10^{19}\ \text{m}^{-3}$.

The 95% confidence limits on the multiplying factor and the indices in the order in which they appear are: ±50%; ±13%; ±14%; ±18%; ±16%; ±15%; ±11%; ±67%.



	I_p/MA	B_T/T	R/m	a/m
(a)	3	3.4	3	1.1
(b)	2	3.4	3	1.1
(c)	4	3.4	3	1.1
(d)	3	2.5	3	1.1
(e)	2.5	1.7	3	1.1
(f)	1	2.5	3.4	0.8
(g)	1	2.9	2.5	0.8

FIGURE 5. Global energy replacement time plotted as a function of mean density. The dashed line is $\tau_E = 7.1\times10^{-22}\,\bar{n}_e a^{1.04} R^{2.04} q_{cy}^{0.5}$ (Goldston 1984) with $a = 110$ cm, $R = 300$ cm, $q_{cy} = 4$.

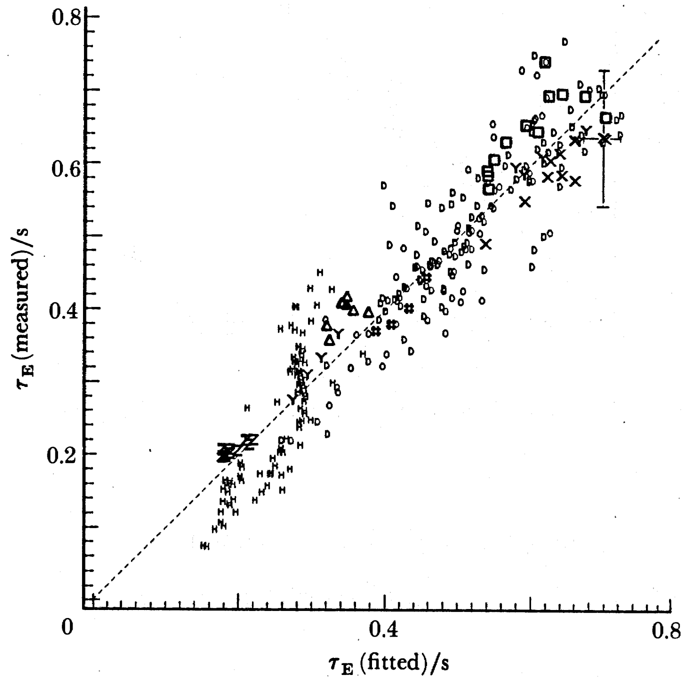


FIGURE 6. Regression fit to energy-replacement time data.

4. COMPARISON OF CONFINEMENT TIME SCALING WITH THAT OBSERVED FOR DISCHARGES WITH OTHER FORMS OF HEATING

Other papers in this symposium discuss the first measurements of confinement time for discharges with radio-frequency and neutral-beam heating. At first sight, the scaling of this data appears to conflict with that in figure 6. However, in making this comparison, it must be remembered that there are constraints in the ohmic data. In particular, the ohmic-power input is a systematic function of the controlled parameters n, q, B_T, R, a, etc. We shall show that when this constraint is taken into account, the data from ohmic- and radio-frequency-heated discharges can be encompassed by the same scaling, suggesting that the same physical energy transport mechanism is at play in both cases. There is as yet insufficient data from neutral-beam-heated discharges to include them in the comparison.

A regression fit to the power input for a representative sample of ohmic heating discharges is shown in figure 7. It will be seen that the data is a good fit to the regression line shown (dashed), which is:

$$P = \text{const.} \times n^{0.07} q_{cy}^{-1.48} B_T^{1.07} (b/a)^{1.24} R^{0.38} (a/R)^{1.23}, \tag{2}$$

where P is the (ohmic) input power.

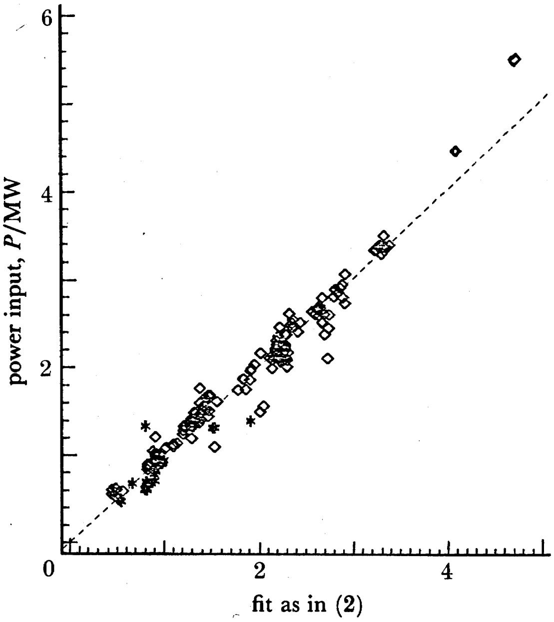


FIGURE 7. Regression fit of power input in ohmic discharges. The dashed line is the fit in (2).

Using the definition:

$$q_{cy} \propto (aB_T/I_p)\,(a/R)\,(b/a) \quad \text{to eliminate } B_T,$$

we have

$$k_p\, q_{cy}^{-0.41} I_p^{1.07} P^{-1} a^{-0.69} (a/R)^{-0.22} n^{0.07} (b/a)^{0.17} = f(P) = 1, \tag{3}$$

where k_p is a constant.

Thus the ohmic data is represented by the fit in (1) and over this data set the quantity (3) is a constant. Hence we can generate an equally good fit to the ohmic data by multiplying (1) by any function of $f(P)$ in (2). If we choose $f(P)^{0.5}$ as the multiplier and drop the dependence on A, which was not tested in (2), then

$$\tau_E \propto n^{0.43} B_T^{0.57} I_p^{0.54} P^{-0.5} R^{2.85} (a/R)^{1.25} q_{cy}^{0.12} (b/a)^{0.3}. \tag{4}$$

or approximately,

$$\tau_E \propto n^{0.4} (I_p\, B_T/P)^{0.5}\, R^3 (a/R)^{1.3}. \tag{5}$$

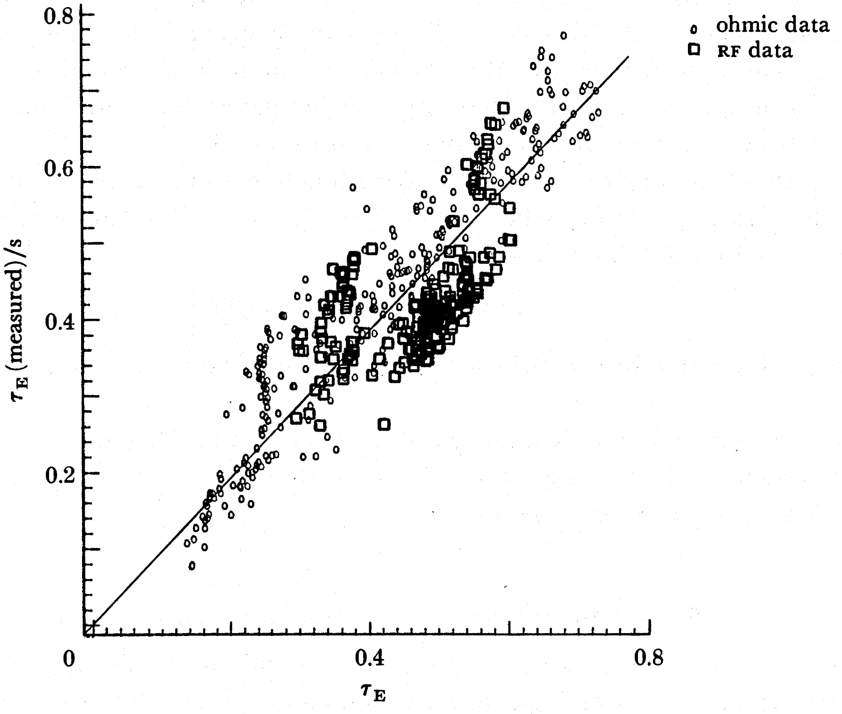


Figure 8. Ohmic and RF data plotted according to the relation in (4). Note that both ohmic and RF data are well represented by the line, which is (4); $\tau_E = \tau_E$ (ohmic fit) $f(P)^{0.5}$, i.e. $\tau_E \propto n^{0.4}\ (I_p B_T/P)^{0.5}\ R^3(a/R)^{1.3}$, approximately.

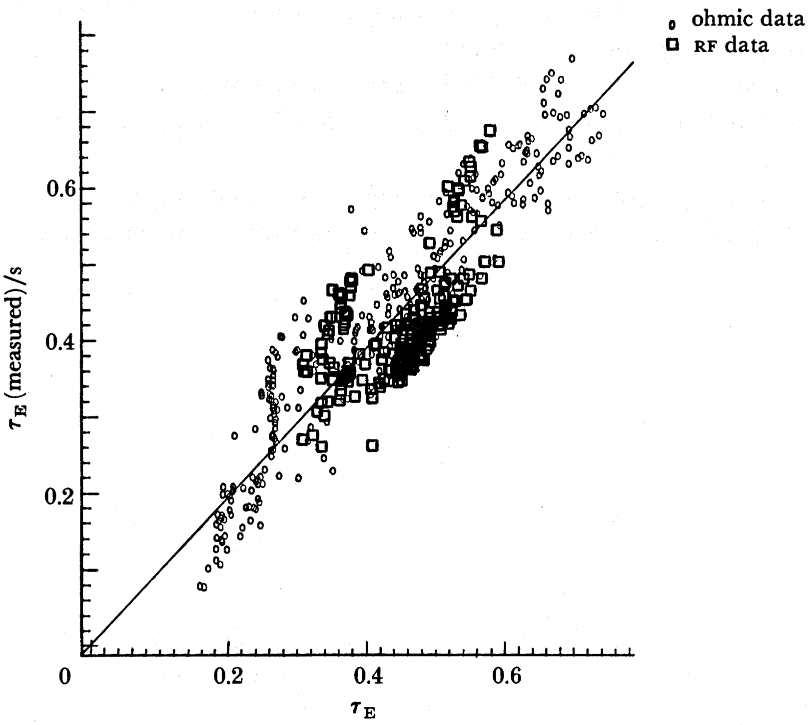


Figure 9. Ohmic and RF data plotted according to the relation in (6). Again both the ohmic and RF data are well represented by the line, which is (6); $\tau_E = 0.02\ \mathrm{s} + (\tau_E(\text{ohmic fit}) - 0.2) f(P)$.

The relation (4) is plotted in figure 8 for all the ohmic data in figure 6 together with the data from radio-frequency-heated discharges (for these discharges P is the total power input: ohmic plus RF). It will be seen that with this choice, the ohmic fit expressed in this way is also a reasonable fit to the RF data. Note that in producing figure 8 no additional constant beyond that obtained by regression in figure 7 has been introduced.

Of course the choice of $f(P)^{0.5}$ as a multiplying function is to a degree arbitrary and has been taken just because it gives a fit to the RF data. With the present limited range of RF power other choices are equally valid. Thus if we take

$$\tau_E = C + [\tau_E(\text{ohmic fit}) - C] f(P), \tag{6}$$

with C chosen by trial to be $C = 0.2$ s we can obtain an equally good fit to the data as is shown in figure 9.

With present range of data it is not possible to choose unambiguously between fits such as (4) and fits such as (6), but there are indications that (6), where the decrease of τ_E with P flattens out a large power, is to be preferred.

5. Conditions for an approach to ignition

Global considerations give a useful guide to the requirements for approaching ignition in a reacting plasma. The power (P_{req}) in watts that has to be supplied to a reacting D–T plasma whose internal energy is increasing at a given rate with central temperature T_0 and central density n_0 is:

$$P_{req}/cV = f_1[\dot{E}_0 + 3n_0 T_0/\tau_E] - 10^{-21} n_0^2 T_0^2 f_\alpha, \tag{7}$$

where other units are metres, seconds and kiloelectronvolts; $c = 1.6 \times 10^{-16}$, $E_0 = 3n_0 T_0$, V is volume and f_1, f_α are geometry factors.

We have used $\langle \sigma v \rangle = 1.13 \times 10^{-24} T^2$ as an approximation to the D–T fusion reaction rate, this is correct to 20% in the range $8 < T < 25$ keV. We shall take $\dot{E}_0 = 3n_0 T_0/2\tau_E$, i.e. E_0 e-folds in $2\tau_E$.

Solutions of (1) have the form shown in figure 10. There is a maximum power required at the point M and a point SS where the temperature would escalate with no external heating source.

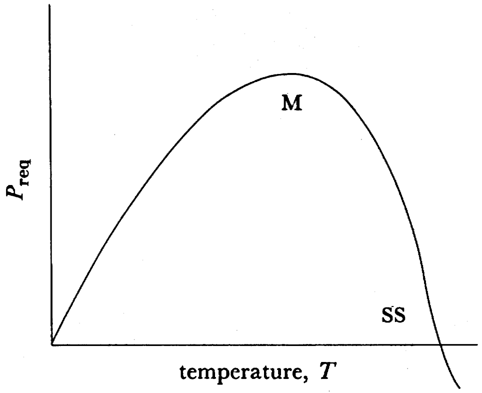


Figure 10. Schematic diagram of the power required (P_{req}) to maintain a given temperature (T) in a reacting plasma according to (7).

If we use JET parameters with the fairly peaked profiles:

$$n/n_0 \text{ and } T/T_0 = (1-x^2)^{\rho}, \quad \text{with} \quad \rho_n + \rho_T = 2.$$

We obtain

$$(P_{\mathrm{req}})_{\mathrm{M}} = 70/\tau_{\mathrm{E}}^2 \ \mathrm{MW}, \tag{8}$$

$$(n_0 T_0 \tau_{\mathrm{E}})_{\mathrm{M}} = 3.7 \times 10^{21},$$

$$\beta_{\mathrm{m}} = 0.085/\tau_{\mathrm{E}}. \tag{9}$$

The quantity β is, as usual, the ratio of plasma to magnetic pressure over the plasma volume and $n_0 T_0 \tau_{\mathrm{E}}$ is a useful figure of merit for the approach to ignition.

It should be noted that the power required increases inversely with the square of the confinement time. However, in any given configuration, equilibrium and stability considerations impose an upper limit to β so that, because of (9), low values of τ_{E} cannot simply be compensated by increasing the input power.

Two specific examples for JET are given below.

(*a*) At the point M, where α-heating is dominant

$$n_0 T_0 \tau_{\mathrm{E}} = 3.7 \times 10^{21},$$

$$\tau_{\mathrm{E}} = 1.7 \ \mathrm{s},$$

$$\beta = 5\%.$$

Ratio of α-particle power to loss power $(P_{\alpha}/P_{\mathrm{loss}}) = 0.74$. Maximum power required (at M) = 24 MW.

(*b*) At lower values of τ_{E} and β, where the α-particle heating, although no longer dominant, is still important:

$$n_0 T_0 \tau_{\mathrm{E}} = 7 \times 10^{20},$$

$$\tau_{\mathrm{E}} = 0.7 \ \mathrm{s},$$

$$\beta = 2.3\%$$

$$P_{\alpha}/P_{\mathrm{loss}} = 0.14.$$

Power required to sustain this condition = 48 MW.

These two examples are both technically possible in JET, provided that the required energy-replacement time can be obtained. Clearly the energy-replacement time of 0.7 s is the smallest that can give a realistic examination of (*d*) in §1.

6. Problems and prospects

6.1. *Impurities*

The impurity behaviour in JET is discussed elsewhere in this symposium. For our purposes it is sufficient to note that with suitable techniques of vessel-wall conditioning (i.e. coating with carbon) and operating at densities in excess of $2 \times 10^{19}\ \mathrm{m}^{-3}$ we can obtain acceptable concentrations of metal impurities (less than 0.02%). It is an important part of the future programme to maintain these low levels as the input power is increased.

The low-atomic-number impurities are present in larger concentrations, i.e. 1–2% of oxygen and 2–4% or carbon. This does not lead to unacceptable radiation levels but it does lead to undesirable dilution of the hydrogen isotope content of the plasma $(0.5 < n_{\mathrm{D}}/n_{\mathrm{e}} \gtrsim 0.7)$. Other types of wall preparation are being examined to reduce this problem.

6.2. *Density limitations*

The present limits to plasma density in ohmic operation are shown in figure 4. They are about a factor of three too low to meet the requirements of §5 with reasonable values of T and τ_E. It is expected that operation with non-ohmic heating and the use of injected pellets of solid deuterium as a fuelling method will lead to higher densities. First results on both these techniques are expected during 1986 with more extensive data in 1987.

6.3. *β values*

The global considerations in §5 imply that β values in the region 3–6% will be necessary. Calculations by Troyon (1984), supported by measurements on many existing tokamaks indicate that, with a plasma current of 5 MA in JET, a β of 3% will be possible. If currents of 7 MA can be obtained then a β of 5% will be possible. Modifications are in hand to permit 7 MA operation in 1987. Thus it appears likely that the required β values will be possible in the JET configuration.

6.4. *Confinement*

We have seen that the behaviour of the energy-replacement time in ohmic discharges JET is now well established over a wide range of parameters and leads to times (greater than 0.7 s), which would be acceptable for fusion experiments. However, when additional heating is used we have seen on JET and other tokamaks that these times are reduced. Goldston (1984) has examined the scaling of energy replacement time in many smaller tokamaks with additional heating he obtains a relation of the form

$$\tau_E = C I_p P^{-0.5} R^{1.38} (R/a)^{0.37} (b/a)^{0.5} \ldots, \tag{10}$$

where he finds $C = 6.4 \times 10^{-8}$ (units: amps, watts, cgs).

The values given by this expression for JET are similar to the values obtained in the first additional heating experiments. For the future operation of JET, say, $I_p = 5$ MA; $P = 30$ MW the predicted τ_E is 0.3 s, clearly too small for the requirements of §5.

A number of possibilities are being explored in the JET programme to increase this confinement time. One such possibility is based on the observation by Keilhacker *et al.* (1984) that an improved confinement behaviour (the so called H-mode) can be produced in plasmas that are bounded by a magnetic separatrix, rather than by a material limiter. The scaling reported by Keilhacker *et al.* (1984) on the ASDEX experiment was

$$\tau_E(s) = 0.16 I_p \text{ (MA)}. \tag{11}$$

If, in addition, we assume an increase proportional to dimension this would predict $\tau_E = 1.5$ s for this configuration in JET with $I_p = 4$ MA. It is thus encouraging that such a configuration has been produced in JET at a current of 2.4 MA, see figure 11. Modifications are in hand to permit similar configurations at currents up to 4 MA. So far only ohmic-heating experiments have been made with these configurations in JET. The confinement behaviour is then equal to the best ohmic discharges with limiters. Experiments with substantial additional heating are planned for later in 1986, whereas experiments with higher currents and powers will take place in 1987.

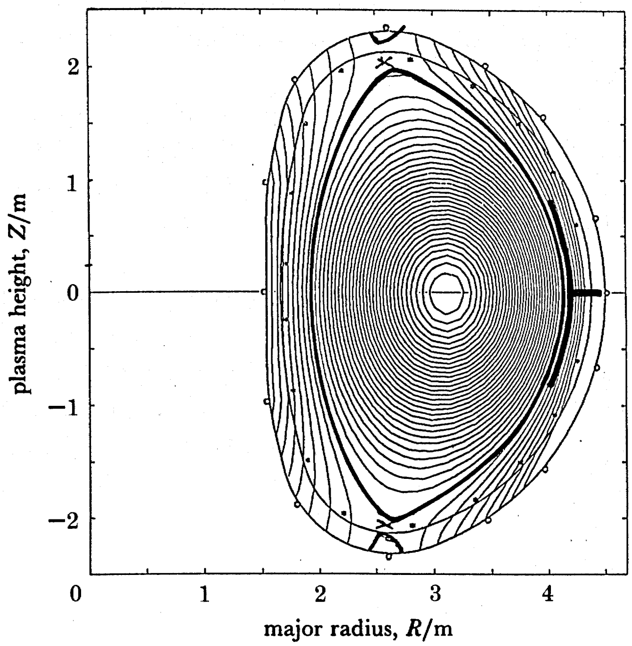


FIGURE 11. Magnetic Surfaces in a JET discharge with a separatrix forming a magnetic limiter defining the plasma edge. In this example the plasma current is 2.4 MA. Modifications are in hand to allow similar configurations to be produced at higher currents.

7. SUMMARY

Experiments with ohmically heated plasmas have produced very encouraging parameters:

$$\begin{aligned} T_{\text{ion}} &\approx 3\ \text{keV}, \\ \tau_{\text{E}} &\approx 0.8\ \text{s}, \\ n_{\text{e}} &\approx 4 \times 10^{19}\ \text{m}^{-3}, \\ (n_{\text{D}} &\approx 2.5 \times 10^{19}\ \text{m}^{-3}) \\ n_{\text{D}}\,\tau_{\text{E}}\,T_{\text{i}} &\approx 0.6 \times 10^{20}\ \text{m}^{-3}\ \text{s keV}. \end{aligned}$$

The last parameter is to be compared with 5×10^{20} needed for significant α-heating and 4×10^{21} required for full ignition.

These results, together with results from other tokamaks, show considerable promise for the future.

Near ignition on JET requires:

$$n_0\,T_0\,\tau_{\text{E}} = 3.7 \times 10^{21}\ \text{m}^{-3}\ \text{s keV}: \tau_{\text{E}} \approx 1.7\ \text{s};\ \beta_{\text{T}} \approx 5\,\%;\ P \approx 25\ \text{MW},$$

whereas significant α-heating would be possible with

$$n_0\,T_0\,\tau_{\text{E}} = 7 \times 10^{20}\ \text{m}^{-3}\ \text{s keV}: \quad \tau_{\text{E}} \approx 0.7\ \text{s}; \quad \beta_{\text{T}} \approx 2.3\,\%; \quad P \approx 48\ \text{MW}.$$

Achievement of these conditions in JET will require improvements in the present performance, perhaps by changing the mode of operation, perhaps by the addition of further external equipment to modify the plasma behaviour.

Important problems to be addressed in this way in the coming years are:

(*a*) the control of loss processes that develop when large amounts of additional heating are applied to the plasma;

(*b*) the control of impurities as wall loadings increase with additional heating;

(*c*) the achievement of high plasma densities in a manner consistent with the controlled termination of the discharge.

If the correct conditions can be obtained, the design of the JET apparatus, its diagnostic equipment, the buildings in which it stands and the provision which has been made for remote maintenance are all such that an extensive series of experiments on a reacting D–T plasma can begin in the early 1990s.

The work reported in this paper has been made possible by the efforts of JET project and associate staff involved in construction, operation, measurement and theory. I am particularly grateful to the following for making available results of their own, including many of the diagrams in the paper: D. Barlett, R. J. Bickerton, K. Berhringer, M. Bures, D. Campbell, J. Cordey, A. Costley, G. A. Cottrell, L. de Kock, C. W. Gowers, J. Jacquinot, P. Lallia, E. Lazzaro, P. H. Rebut, R. Ross, C. Schüller, A. Tanga, P. Thomas, K. Thomsen and G. Tonneti.

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