ENERGY TRANSPORT IN JET WITH OHMIC AND AUXILIARY HEATING

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JET has now been operated with ohmic, ion cyclotron resonance and neutral beam injection heating. A wide range of plasma conditions have been studied with ohmic and ion cyclotron resonance heating while neutral beam injection heating has just recently been applied.

1. OHMIC HEATING

During 1984 and 1985 an extensive series of experiments with ohmic heating have been carried out in both Hydrogen and Deuterium discharges [1].

The ranges of variation in the main plasma parameters covered are: Toroidal magnetic field $1.7 < B_T < 3.4$ T; plasma current $1 < I_p < 4$ MA; line average density $0.5 \times 10^{19} < n < 3.6 \times 10^{19}$ m^{-3}; elongation $1 < K$ (= b/a) < 1.7; minor radius $0.8 < a < 1.23$ m; major radius $2.5 < R < 3.4$ m; cylindrical safety factor $1.7 < q < 12$; effective charge $2 < Z_{eff} < 8$; peak electron temperature $1.5 < T_e < 5$ keV; peak ion temperature $1 < T_i < 3$ keV.

The plasma geometry has been varied from fully elliptical to small circular plasmas limited on the inside wall or on the limiter. The discharges had long flat tops in current, density and temperature, 4 - 12 secs, which was sufficient in all but the 3.5 and 4 MA discharges for the magnetic field diffusion to have been completed before the end of the flat top. Values up to 0.8 s have been achieved for the energy confinement time defined by $\tau_E = W/(P_{tot} - \dot{W})$, where $W = 3/2 \int (n_e T_e + n_i T_i)\, dv$.

The scaling of τ_E with density for a few characteristic conditions is shown in Fig. 1. The general pattern is that at low densities the confinement time increases roughly linearly with density and then saturates at higher densities ($n \geq 3 \times 10^{19}$ m^{-3}). The precise reason for the saturation is not clear, both the impurity radiation and transport losses increase as the limiting τ_E is reached. Due to the large errors in separating the ion and electron losses at high densities, it is not possible to determine which is the dominant loss channel.

The scaling of τ_E with the plasma parameters has been investigated, Fig. 1 shows that the neo-Alcator scaling, $\tau_E \propto nqR^2a$, is a reasonable fit. A marginally better fit can be obtained by a regression analysis in the form $\tau_E \propto B_T^{\alpha} q^{\beta}$ etc. The result from such an analysis is (A is the atomic mass and $\varepsilon = a/R$ the inverse aspect ratio)

$$\tau_E = 0.013\, n^{0.38}\, q^{0.33}\, B_T^{0.57}\, K^{0.21}\, R^{3.2}\, \varepsilon^{1.7}\, A^{0.56} \qquad (1)$$

The range of variation of R and ε in the JET data set is very small so the uncertainty on their indices are rather large. The JET data set has been combined with the DIII data set to get a better estimate of the scaling with dimensions. The scaling law obtained from a regression analysis on this combined data set can in terms of q (cylindrical) be written as:

$$\tau_{Ee} \propto n^{0.6}\, q^{0.5}\, B_T^{0.1}\, K^{0.3}\, R^{3.4}\, \varepsilon^{0.9} \qquad (2)$$

From analysis of the local transport properties with interpretative and predictive codes three distinct regions have been clearly identified; an inner region dominated by sawtooth activity, an intermediate region dominated by electron and ion thermal transport and an edge region dominated by impurity radiation and other atomic processes. The main loss channel at low and moderate densities in the second region is found to be via the electrons. The ion thermal conductivity is between 1 and 8 times neoclassical with the higher values of this anomaly factor occuring at lower densities. The electron thermal conductivity can be approximated by $\chi_e \sim 2.5.10^{19}/n$ at low densities, while for the highest JET densities it does not decrease with n. No clear dependence of χ_e on toroidal magnetic field or plasma current has been observed so far.

2. ION CYCLOTRON RESONANCE HEATING

Ion cyclotron resonance heating has been used in JET since the beginning of 1985. The heating system and characteristics of the different antennas are described elsewhere [2]. Various minority heating experiments have been performed in deuterium discharges with either H or ^3He as the minority gas.

It has been possible to couple up to 6 MW of RF power, P_{RF}, to the plasma. The increase of the total plasma energy during ICRH is partly due to a density increase. However, both the ion and electron temperatures have also been increased significantly.

In the first experiments the power scaling of W and τ_E was unclear [3]. Recent results seem to support a linear scaling of W with power in the form

$$W = W(o) + \tau_{inc}\, P_{tot} \qquad (3)$$

Fig. 2 shows W versus P_{tot} for different plasma currents obtained in D (^3He) limiter discharges with $B_T = 3.4$ T, $K = 1.45$ and $a = 1.2$ m using a frequency of 33 MHz for central power deposition. The results of fitting eq. (3) to the RF-points only are shown by dotted lines. The incremental confinement time τ_{inc}, obtained this way, ranges from 128 ms - 192 ms with no obvious current dependence.

At present no strong dependencies of τ_{inc} with respect to P_{RF}, B_T, I_P and n_e have been observed, however, comparing with results from other tokamaks there must clearly be a strong dependence on the plasma size [4]. The degradation of the total τ_E during ICRH is clearly seen in Fig. 3.

From Eq. (3) we may express the confinement of both ohmic and additional heated plasmas in the form

$$\tau_E = \tau_E^{OH} \frac{P_\Omega(0)}{P_{tot}} + \tau_{inc} \left(1 - \frac{P_\Omega(0)}{P_{tot}}\right) \quad (4)$$

where τ_E^{OH} and $P_\Omega(0)$ are the ohmic heating confinement time and power, respectively, in the absence of auxiliary heating. The present τ_{inc} is typically one third of τ_E^{OH}, which means we need to couple more than 10 times the ohmic power in order to confirm the saturation of τ_E.

By performing an exponential fit of the form $W(t) = W_o + \Delta W\ (1-\exp(-t/\tau))$ to the time evolution of W from the time of a change in RF-power level, we can estimate the fraction $f = (\Delta W - \tau\Delta P_\Omega)/\tau\Delta P_{RF}$ of RF-power which contributes to the increase in stored energy. This fraction f was typically ~ 70% in the experiments shown in Figs. 2, 3.

3. NEUTRAL BEAM INJECTION HEATING

Neutral beam injection heating (45 - 65 keV H into D plasma) has now been successfully applied to JET discharges [5]. Identical target plasmas have been used for NBI and ICRH making it possible to compare the two methods. Fig. 4 shows W versus P_{tot} for NBI heating, i.e. the equivalent of Fig. 2. Again a linear dependence of W with P_{tot} (eq. (3)) fits the data. In addition τ_{inc} shows an apparent current dependence which is present in all the estimates of the total plasma energy as is shown in Fig. 5.

In conclusion all NBI and ICRH experiments so far have produced values of τ_{inc} in the range 100 - 300 ms. Future heating experiments with more input power are needed to determine the dependence of τ_{inc} with power.

REFERENCES

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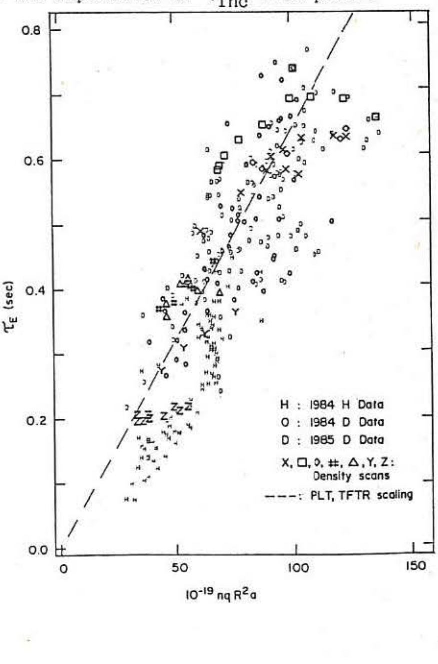

Figure 1 : Energy confinement time versus the neo-Alcator scaling. Ohmic data only.

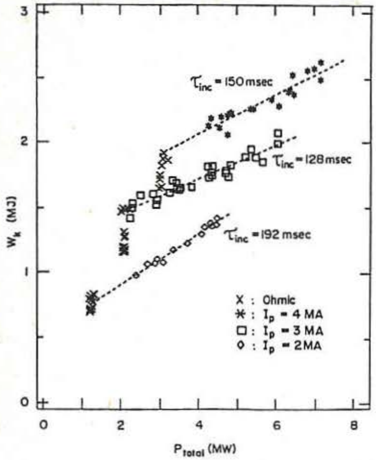

Figure 2 : Total kinetic plasma energy versus total input power from ICRH heating experiment.

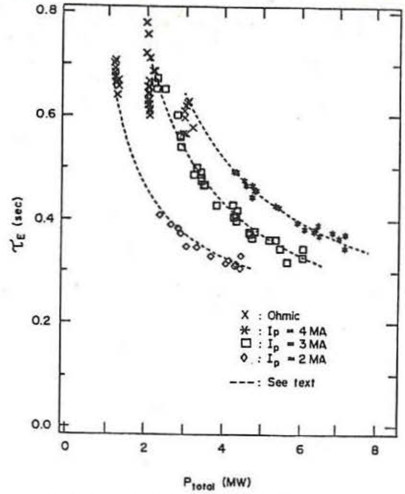

Figure 3 : Energy confinement time versus total input power from ICRH heating experiment. The dotted lines correspond to the fit lines in Fig. 2.

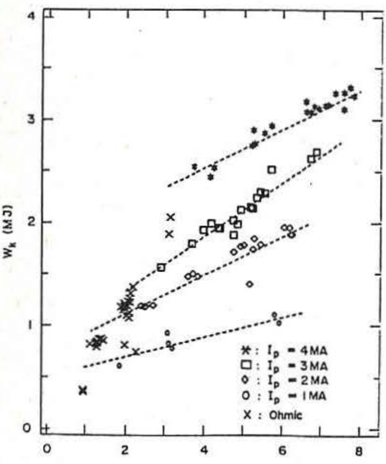

Figure 4 : Total kinetic plasma energy versus total input power from NBI heating experiment. The results of fitting the data to Eq. (3) are shown by dotted lines.

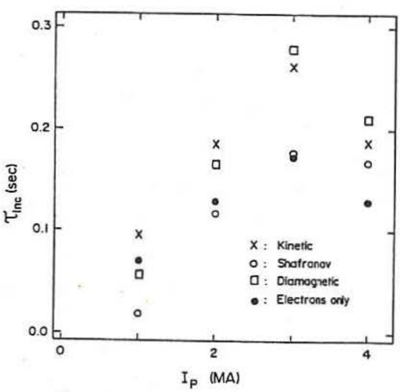

Figure 5 : The incremental confinement time, determined from the different estimates of plasma energy, shown versus plasma current, for the NBI heating experiment.