Scaling of Ion Parameters at the H-Transition in JET

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Introduction

Shaing *et al.* have proposed a theory of the H-mode based on bifurcated solutions for poloidal flow[1]. In this theory the driving mechanism for poloidal flow is ion orbit loss. It is predicted that as the ion collisionality, ν_i^* is reduced below some (machine dependent) threshold close to unity the poloidal flow speed will suddenly increase, establishing the H-mode.

Experiments on DIII–D[2] involving a neutral beam power scan agreed with the predictions of the theory. ν_i^* depends on T_i^{-2}, thus the critical collisionally appeared as a critical T_i in the experiment.

We report here on a series of experiments on JET aimed at testing this critical ν_i^* prediction. In these experiments ν_i^* was varied by changing the density in a sequence of discharges with constant neutral heating power.

Experiment

A series of discharges were made with target volume average density varying between 8 and $20\times10^{18}\,m^{-3}$. The discharges had the same injection power profile with $7\,MW$ NBI for $600\,ms$ used to establish the H-mode, reduced to $2\,MW$ for $200\,ms$ to allow charge exchange measurements at the back transition. Plasma parameters from one of these discharges are shown in figure 1. The discharges were $2.6\,MA$, $2.8\,T$, double null, without sawteeth: a sawtooth crash is frequently the trigger for the H-mode. Edge ion temperatures and densities were measured by charge exchange spectroscopy of carbon impurities.

In these sawtooth free discharges the H-mode transition is not accompanied by a sharp drop in D_α, instead the D_α signal exhibits a period of rapid 'dithering' before becoming quiet, as shown in figure 1. In this analysis we consider two times; the start and the end of the dithering phase at the transition, t_{LD} and t_{DH}. Some shots show a sudden jump up in the edge ion temperature at the first time, suggesting that this is the true start of the H-mode. The trend in both times over the density scan is the same.

In the low density shots the transition to H-mode occurs later than in the high density shots. The duration of the H-phase is also shortest at low density. Since the ion temperatures show little shot to shot variation the low density shots have lower collisionality, thus the theory[1] predicts the opposite trend to that seen in these experiments.

This simple interpretation ignores the effect of impurities on the ion viscosity. The standard neoclassical expression for viscosity can be modified to include ion-impurity collisions and impurity-impurity collisions[3]. By analogy we modify the collisionality expression used in [1], including impurities,

$$\nu_i^{\star} = \frac{\nu_{ii} R q}{v_t \epsilon^{3/2}} \left\{ 1 + 2\sqrt{2} \frac{n_z}{n_i} Z^2 + \left(\frac{n_z}{n_i} \right)^2 Z^4 \sqrt{\frac{m_z}{m_i}} \right\} \tag{1}$$

The inclusion of the impurity terms can significantly affects the results if n_z is more than 2% (in the case of carbon). The effect on our results is that the behaviour of n_z tends to compensate for the reducing n_i during the density scan. The $\nu_i^{\star}$ curves are nearly coincident throughout the sequence of discharges, although there remains a weak trend of decreasing $\nu_i^{\star}$ at the transition with decreasing density, figure 2.

Although this more detailed evaluation of $\nu_i^{\star}$ affects the simple trends the results are still at variance with a critical collisionality hypothesis. The collisionality at the back transition is significantly lower than that at the H-transition, which is also counter to this hypothesis.

Validity of Parameters

In the evaluation of (1) we take n_z from the edge charge exchange measurements, and n_i as $n_e - n_z Z$. The edge carbon density was typically 2% in these discharges; measurements in the discharge centre showed that it was the dominant impurity.

Electron density was measured with a multichord interferometer and also a reflectometer. The interferometer relies on an inversion of the chordal data and an imposed boundary condition of zero density at $\rho = r/a = 1.01$. The reflectometer measures the position of a number of critical density layers and can measure the edge density profile in detail. However the reflectometer also depends upon an inversion procedure and for many times in these discharges the data cannot be analysed. The electron density profiles from the interferometer are rather flat both before and after the H-mode transition in these discharges. The reflectometer data, when available, confirms the accuracy of the interferometer reconstructions within about $\rho < 0.95$. The electron density at 4.0 m (5–7 cms inside the separatrix) was taken to be 0.75 $<n_e>$ (the volume averaged n_e). When compared to the profile data this approximation was found adequate. (The use of this expression is simply a convenience since the interferometer profiles are reconstructed on different spatial grids for the different discharges, dependent on the position of the separatrix. $<n_e>$ however is independent of the separatrix position.) The expression for n_e then represents n_e at a fixed ρ equivalent to about 4.0 m.

The ion temperature was measured from C VI charge exchange emission at a fixed position of 4.01 m. The separatrix position was 4.06 m but varied within ±1.5 cm shot to shot, and drifted by up to 2 cm inwards over the course of the H-mode. The measured ion temperature gradients were at most 30 $eV.cm^{-1}$ so the movements of the separatrix are not significant. The value of T_i can thus be regarded as the temperature at a fixed ρ. The equilibration time of impurity ion temperature is calculated as of order 100 μs, far shorter than the timescales of ion heating, suggesting that the impurity ion temperature is equal to the fuel ion temperature.

Measurements of edge electron temperature were made using the microwave heterodyne radiometer. Measurements obtained within 1 cm of the radius of the impurity ion temperature measurements showed good agreement with those temperatures. The measured T_i were always equal to or lower than those of T_e with the biggest differences (at the highest temperatures) reaching 25%. The differences in temperature were less than 10% at the times of the H-mode transitions.

Scalings

From the D_α traces up to four times may be associated with these H-modes. These are the start and end of the dithering phase at the H-transition, t_{LD} and t_{DH} referred to above, and the start and end of the dithering phase of the back transition, t_{HD} and t_{DL}. In several discharges the times of the back transition are impossible to define accurately, and for the longer duration H-modes the back transition occurs after the cessation of NBI, so no charge exchange data is available.

Despite these caveats the ion parameters at the four times form a usable dataset. From this data it found that the values of $\nu_i^\star$ at the H-transition vary from 1.3 to 5.0 at t_{LD}, and from .7 to 1.5 at t_{DH}. Similarly the values of edge T_i at transition vary from 220 to 580 eV at t_{LD}, and from 540 to 1000 eV at t_{DH}.

Figure 3 shows the parameter $Z_{\mathrm{eff}}.T_i^{-\frac{3}{4}}$ at the four transitions plotted against the time of the transition (where Z_{eff} has been derived from n_e and n_z at the edge). The value of this parameter is remarkably constant at the start and end of the quiescent phase. It is somewhat less constant at the start of the dithering phase, although much of the scatter in the values here is due to the poorer determination of T_i and n_z when the carbon density is still low.

Conclusions

The results of these experiments show that the value of $\nu_i^\star$ at the H-mode transition, while always close to unity, is not constant as a function of density. The addition of impurity collisions in the expression for $\nu_i^\star$ makes a significant difference to the interpretation of the data. There is a clear requirement for the full inclusion of impurities in the viscosity of [1]. The threshold for H-mode in these experiments is well described by $Z_{\mathrm{eff}}.T_i^{-3/4}$, an expression closely related to that for $\nu_i^\star$.

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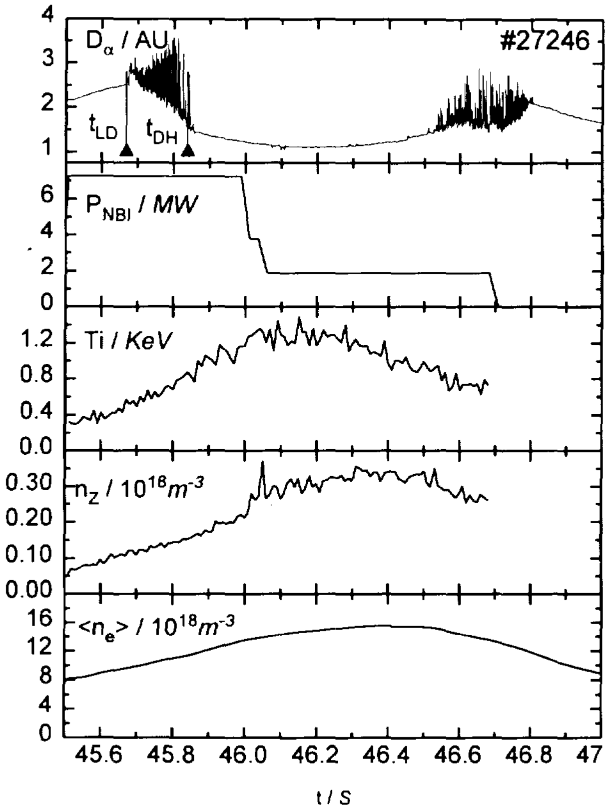

Figure 1: D_α and plasma parameters for one of the H-mode discharges used in the density scan. The start of the dithering and the quiet H-mode phases can be seen clearly.

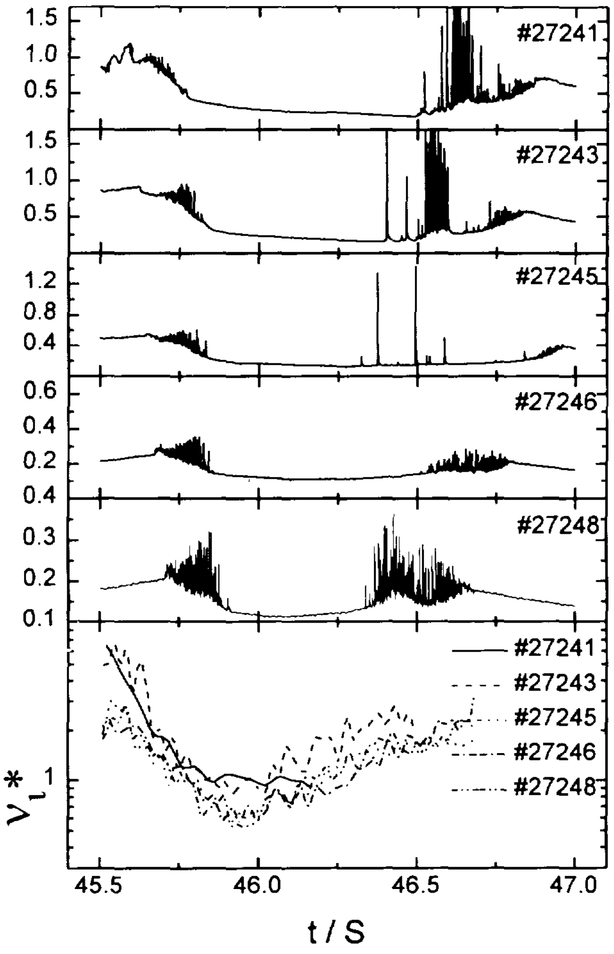

Figure 2: D_α traces and calculated ion collisionalities for some of the shots in the density scan. Density decreases from the top to the bottom of the figure. There is little variation in the time behaviour of ν_i^* in the different discharges, although the lower density discharges tend to have lower collisionalities.

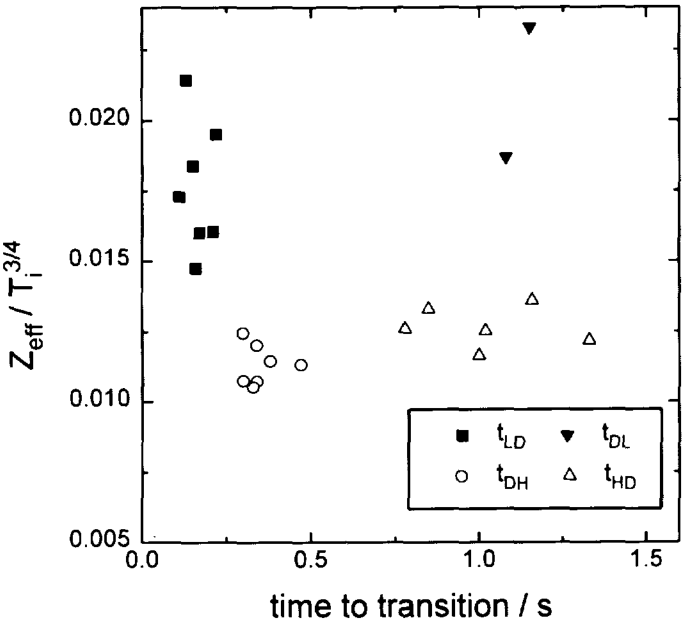

Figure 3: Scatter plot of the quantity $Z_{\text{eff}}/T_i^{3/4}$ at the four transition times.