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Effects of temperature ratio on JET transport in hot ion and hot electron regimes

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The basic reason for the interest in effects of the temperature ratio Te/Ti on tokamak transport is the fact that most present day high performance shots have strong ion heating while a burning machine, like ITER, will have most of the heating on electrons. In order to try to understand the importance of the temperature ratio, two series of JET shots, one in the hot ion regime provided by Paul Thomas[1] and one in the hot electron regime provided by Wolfgang Suttrop[2] have been analysed by predictive transport simulations. The hot electron regime was analysed in Ref 3. In the present work the main focus will be on the hot ion regime.

The transport model used has been the Weiland drift wave model[4]. This model includes the Ion Temperature Gradient (ITG) mode, the Trapped Electron (TE) mode, the impurity ITG mode, the Kinetic Ballooning (KB) mode and the Magnetohydrodynamic (MHD) ballooning mode. The ITG mode includes both slab and curvature (toroidal) drive and the TE mode can both be driven by the density gradient (Ubiquitous mode) and by the electron temperature gradient (compressional TE mode). The compressional TE mode usually is the most important TE mode in the bulk of H-mode plasmas due to the flat density gradients there. It is essentially symmetric to the ITG mode and thus has a dispersion relation similar to that of the Electron Temperature Gradient (ETG) mode which is, however, not included. Its threshold is not expected to be reached by the gradients occurring in the experiments studied here. The transport coefficients include a full transport matrix including possibilities for fluxes that increase gradients (pinches).

Basis of ITG and TE mode scalings: In the flat density tokamak core the ITG and TE modes are basically resonant modes associated with fluid resonances. In this regime they decouple and are in the simplest toroidal case described by quadratic dispersion relations. Including also the dilution on the ITG due to electron trapping (fraction f_t) we have:

ITG (local limit)

$$\omega = \omega_r + \sqrt{\omega_{\bullet e}\omega_{\bullet i}(\eta_i - \eta_{ith})} \tag{1a}$$

$$\omega_r = \frac{1}{2}\omega_{\bullet e}\left[1 - \varepsilon_n\left(1 + \frac{10}{3\tau}\right)\right] \qquad \tau = \frac{T_e}{T_i},\ \varepsilon_n = \frac{\omega_{De}}{\omega_{\bullet e}} \tag{1b}$$

The local ITG threshold without finite Larmor radius effects is :

$$\frac{R}{L_{ti}} = \frac{4}{3\varepsilon_n} + \frac{20}{9\tau}(1 - f_t) - \frac{\tau}{(1 - f_t)\varepsilon_n} + \frac{\tau}{2(1 - f_t)} + \frac{\tau}{2\varepsilon_n{}^2(1 - f_t)} \tag{1c}$$

TE mode

$$\omega = \omega_r + \sqrt{-\Gamma \omega_{\bullet e} \omega_{De} (\eta_e - \eta_{eth})} \tag{2a}$$

$$\omega_r = -\frac{1}{2}\omega_{\bullet e}\left[\Gamma - \varepsilon_n(\Gamma + \frac{10}{3})\right]; \quad \Gamma = \frac{f_t}{1 - f_t} \tag{2b}$$

The threshold is:

$$\frac{R}{L_{Te}} = \frac{4}{3\varepsilon_n} + \frac{20}{9\Gamma} + \frac{\Gamma}{2}(1 - \frac{1}{\varepsilon_n})^2 \tag{2c}$$

We note the trend for the ITG and TE modes to propagate in different directions. The phase velocities have equal magnitudes but opposite signs when f_t =0.5 and τ=1.
It is interesting to note the (quasi) symmetry in phase velocities while the temperature behaviour is asymmetric. The ITG mode is driven by the root of the product of ion and electron drifts while the trapped electron mode is driven by purely electron drifts. This ideal form of the TE mode does not depend on the ion temperature at all. (We note the difference to the Ubiquitous mode which is actually due to a coupling between the present modes). We also note that the threshold of the ITG mode increases in the hot ion regime while that of the TE mode is independent of temperature. The transport code which we will use, of course, includes all couplings and intermediate states between the ”ideal” modes considered above. We, however, expect that confinement will deteriorate when we increase Te while an increase in Ti has two counteracting effects. Both the driving term and the threshold will increase.
Experimental background: It is well known that ion transport is reduced in the hot ion regime. Recent experiments on D-III-D[5] and AUG[6] have shown a very rapid decrease in ion energy confinement when the electron heating is increased in the hot ion regime while the electron temperature is almost constant. The JET shots we study here[1] are from the Tritium campaign. Recent JET shots using ICRH with minority heating[2] have obtained Te/Ti of about 2. These shots do not have the very good confinement of the hot ion regime but are still not far from typical scaling laws.
Simulations: **A**lthough it is well known that the hot ion regime gives reduced transport in ITG models, it has usually been difficult to recover the very high central ion temperature in transport simulations using ITG transport. In the present simulations we have succeeded rather well in most cases. The confinement has been improved by rotation and finite beta effects. The decrease of ion temperature with increased electron heating seen on D-III-D and AUG has been recovered qualitatively by artificially increasing the NBI electron heating in the simulations of JET shots. Transport barriers were obtained by artificially increasing the ion heating also without rotation. Finite beta effects tend to contribute to this by giving an ion heat pinch.
In the hot electron regime, good agreement was, in general, obtained with the temperature profiles of the JET shots in this regime[3]. However strong stiffness was obtained in the simulations when the electron heating was artificially increased by factors 4 or more and we had both ion and electron heating. This could even lead to increasing gradient scale lengths in steady state[3]. No transport barrier could be obtained. Note, however that perturbative simulations close to experimental profiles with only electron heating indicated mild stiffness[7]. The characteristics of gradient profiles were very different in hot electron and hot ion regimes and the hot ion regime gave good confinement. Nevertheless, replacing ion heating by electron heating can be beneficial. This is due to a kind of dilution effect caused by the fact that only

trapped electrons contribute to transport in low beta plasmas.

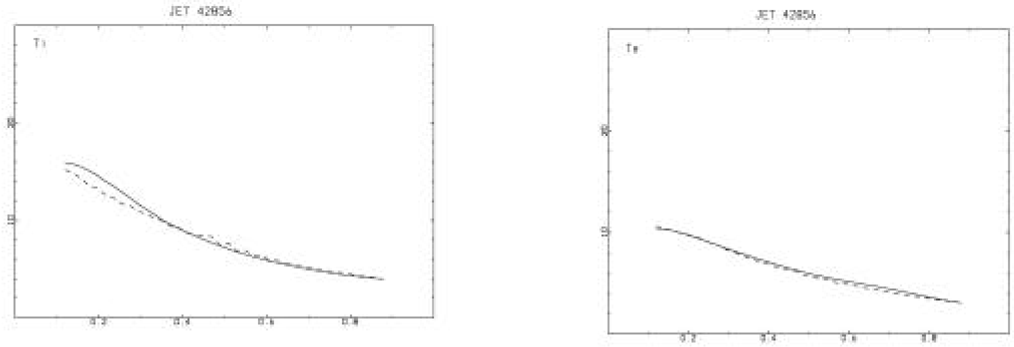

Fig 1. Radial profiles of Ti and Te for JET 42856 (hot ion). Full lines are from experiment and dotted lines from simulation.

The radial profiles of Ti and Te from experiment[1] and simulation for a typical hot ion shot are shown in Fig 1. In this shot the auxiliary heating was only neutral beam with 7.3 MW on ions and 2 MW on electrons. This was a DT shot with alpha power 0.37 MW on electrons. Effects of rotation on Ti are shown as wiggles at half radius. Tests were made by artificially increasing the NBI electron heating with a space independent factor in the simulations. By doubling the electron heating, the central electron temperature increased by 10% while the central ion temperature decreased by 9 %. When the electron heating was multiplied by 4, Te increased by 15% while Ti decreased by 28%. This shows that the electron channel is very stiff while the ion temperature is reduced for increased electron heating. Such qualitative trends have been seen experimentally on D-III-D and AUG. In the simulations the reason for this is a reduction of the threshold of the ITG mode when Te/Ti is increased.

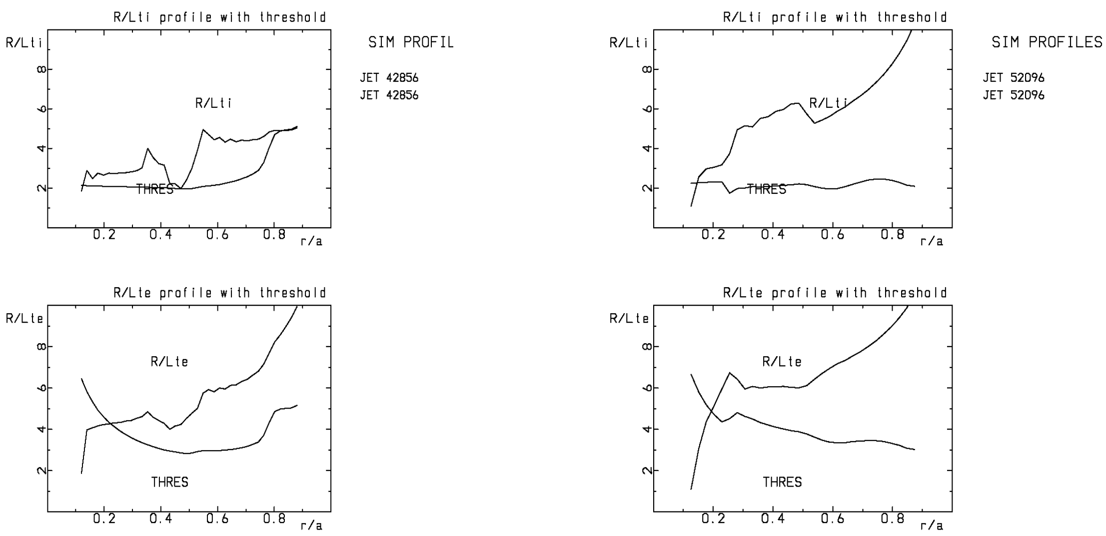

Fig 2. Radial profiles of gradients and thresholds for JET42856 (hot ion) and JET 52096 (hot electron)

As seen in Fig 2 the radial shapes of thresholds of ITG and TE modes and the corresponding experimental gradient profiles of Ti and Te are very different for hot ion and hot electron shots. We have here plotted the local ITG threshold which is similar to the TE threshold. It gives the threshold of the toroidal ITG mode which has the larger growth-rate. The nonlocal threshold is obtained from (1c) by keeping only the first two terms in the r.h.s. We can see that the threshold increases in the hot ion regime for large ε_n. However, here all the terms are contributing. The thresholds of ITG and TE modes are not directly comparable since ε_n also is different. In general the thresholds seem to play a more important role in the hot ion regime since the temperature profiles are closer to threshold. This is more pronounced for the ITG mode than for the TE mode. It is, however, the electron channel that shows strong stiffness in the hot ion regime.

When the ion heating was increased in the hot ion regime, the ion temperature increased strongly and eventually a transport barrier was formed. The simulations in the hot ion regime were very sensitive due to the appearance of transport feedback loops. One such loop is active in connection with an increase of electron heating. Here the increased Te leads to increased Te/Ti which decreases the ITG threshold. This leads to a reduction of Ti and a further increase in Te/Ti. The feedback is terminated when the profiles become sufficiently distant from the threshold. The opposite feedback loop gets activated upon a decrease of electron heating. Another feedback loop involves rotation. An increased density gradient gives increased rotation which gives increased temperature gradient. An increased temperature gradient will, through off diagonal transport fluxes reduce the particle transport and the density gradient is increased. Because of this, transport barriers can sometimes be formed also when the experiment does not have a barrier. This is because of the strongly nonlinear situation giving a possible bifurcation. Thus in some cases either the particle transport or the rotation had to be turned off.

The temperature ratios in the hot electron JET shots were similar to those obtained in ITER simulations[8] using the same transport model. This gives some more confidence in the ITER predictions which gave fusion Q=9 for the reference design when the density profile was frozen.

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