EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(02)02-07

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Preprint of Paper to be submitted for publication in
Proceedings of the 29th EPS Conference, (Montreux, Switzerland 17-21 June 2002)

INTRODUCTION

Turbulence stabilization mechanisms in internal transport barriers (ITBs) observed in tokamak plasmas are not fully understood. The turbulence is related to drift wave instabilities, which, although essentially electromagnetic in nature, are generally studied in the electrostatic approximation. Among the various instabilities associated to drift waves, those which seem to have a role in the formation of ITBs are instabilities driven by the ion and electron temperature gradients (respectively known as ITG and ETG modes). ITG modes, having longer wavelengths, can act on both ion and electron transport. On the contrary, ETG having shorter wavelengths, essentially modify only electron transport. Trapped electron modes (TEM), having wavelengths in the same range as those of ITG modes, represent another possibility of long wavelength instability. Several experiments in JET ion heated discharges show that the appearance of an ITB is linked to ITG mode stabilization. Various mechanisms may be responsible for such stabilization: the main one is thought to be due to E x B sheared flow associated to the presence of a radial electric field. In this frame, the turbulence is stabilized when the shearing rate (ω_s) exceeds the maximum linear growth rate of the instability (γ_{max}). An additional ingredient may be the presence of a null or very low magnetic shear (s) region in the plasma: this helps by reducing the growth rate of the instabilities. Another point that is not completely clear is the triggering mechanism of the turbulence stabilization. A necessary and sufficient condition for triggering an ITB can be the injection of a large momentum (such as provided by Neutral Beam), but there are other experimental situations in which the injected momentum is not enough to explain the occurrence of the turbulence stabilization. In such cases, other trigger mechanisms are often invoked such as the role of rational safety factor (q) surfaces observed in some JET ITBs [1] or, again, the existence of an off-axis s=0 surface in the plasma may be important. In this respect, also ITBs produced in electron heated discharges show a correlation with regions of null or low s: this has been observed in pure electron barriers not only in JET, but also in several other tokamaks such as, for instance, Tore Supra and FTU.

RESULTS

ITG turbulence suppression occurs when the E x B flow shearing rate, ω_s, exceeds the maximum ITG linear growth rate γ_m . ω_s is defined as:

$$\omega_s \cong \left| \frac{RB_\theta}{B_\phi} \frac{\partial}{\partial r} \left(\frac{E_r}{RB_\theta} \right) \right| \qquad (1),$$

where E_r is the radial electric field and B_θ and B_ϕ are the poloidal and toroidal magnetic field An expression for γ_m, valid for low |s|, is obtained by taking into account that at or around the minima and maxima of the safety factor q the overlapping of ITG drift eigenmodes centered on neighbouring rational surfaces is negligible [2]:

$$\gamma_m = (\eta_i - 2/3)^{1/2} |s| c_i / qR \qquad (2),$$

where $\eta_i = L_n / L_T$ and $c_i = \sqrt{T_i / m_i}$ (L_T and L_n being the density and ion temperature gradientlengths). Eq. (2) holds in the limit $\varepsilon_N s / q << 1$ where $\varepsilon_N = L_n / R$. The use of eq. (2) is justified in the majority of JET ITB discharges in the regions of low and not deeply reversed $|s|$. We stress that the the reduction of the density of rational surfaces around s=0 which can reduce the turbulence in such region is the argument underlying eq. (2) and is valid for long wavelenght turbulence ($k_\perp \rho_i<1$). Note that also another formula for γ_m, valid under the hypothesis of large overlap of ITG modes, has been previously used [3].

We analyzed a set of JET ITB discharges (I_p=2.2 MA, B_t=2.6 T, with both NBI and ICRH additional heating) by comparing the $\omega_s > \gamma_m$ condition with the location of the barriers as observed in the experimental T_e and T_i profiles. The dataset includes ITB discharges with i) large negative s, ii) a region of roughly null s and iii) monotonic s. For the evaluation of ω_s and γ_m from the above two formulas, E_r, which is not directly measured in JET at present, is calculated from the plasma radial force balance equation (under the assumption that the poloidal velocities can be expressed according to the neoclassical theory) using experimental ion temperature and carbon impurity toroidal velocity (both provided by charge exchange spectroscopy) and electron density (from LIDAR Thomson scattering), while the q-profiles are produced by the EFIT magnetic reconstruction code constrained with motional stark effect (MSE) measurements. For the same set of discharges, it has already been shown [4] that the power threshold in order to have a barrier (defined as the power such that a clear barrier is obtained according to the $\rho^* > \rho^*_{ITB} = 1.4\text{x}10^{-2}$ criterion - ρ^* being the normalized ion Larmor radius [5]) is lower when LHCD preheat is applied, so that reversed q-profiles are present when the main heating power is injected.

The results of the present analysis are shown in Figs. 1, 2 and 3. It is observed (Figs.1 and 2: two time slices are shown for each discharge) that identical discharges (#51573 and #51598) with same input total power ($P_{TOT}=P_{NBI}+P_{ICRH}$=17 MW) but different q-profiles (flat monotonic/ohmic preheat in #51598, reversed/LHCD preheat in #51573) perform very differently in terms of ITB strength. The discharge (#51573) with a well-defined s=0 surface at about R~3.4 m shows a good barrier correlated with the $\omega_s > \gamma_m$ condition, while the discharge without an off-axis s=0 region performs badly (having a weak barrier, whose location is, however, still correlated with $\omega_s > \gamma_m$). Therefore, the comparison of this kind of similar discharges but with different s behaviour, gives a strong indication that the effect of the magnetic shear is a key point in lowering the growth rate of the turbulence. A discharge with monotonic s is shown in Fig.3 (#51608, ohmic preheat, $P_{TOT}=P_{NBI}$=7.3 MW): in this case the region of low magnetic shear close to the magnetic axis allows the formation of a weak central barrier (visible in the ion profile) at t=6.6 s. This situation here is similar to that of discharge #51598: when there is no clear reversed q-profile, even though there is a region of low s the suppression of turbulence is not enough or marginal and therefore only weak barriers appear unless a very high momentum input is provided. On the contrary, when a well-defined s=0 surface is present off-axis at about mid-major radius there is a substantial growth rate reduction and the possibility of having strong barriers such as those seen in discharge #51573. Such results are representative of the whole dataset we have analyzed.

In addition, the role of the magnetic shear is also highlighted by the study of the temporal evolution of the quantity $s_{ITB} = s(R_{ITB})$, i.e. the value of the magnetic shear at the radial location corresponding to the foot of the barrier (R_{ITB}): R_{ITB} is defined as the first radius (moving from the edge towards the center of the plasma) where the condition $\rho^* > \rho^*_{ITB}$ is verified. It is found that when either a weak or strong barrier forms the magnetic shear s at the radial location of the foot of the barrier is always very close to zero. This fact is satisfied both by electron and ion barriers in the same discharges (Fig.4). By the way, this is also an indication that, in these ITBs, the electron and ion species behave practically in the same way as far as the location and the timing of the transport barriers are concerned.

DISCUSSION

So far, we have considered discharges where ion heating is predominant. However, there are other experimental situations in which transport barriers are observed with electron heating only. There are examples in JET, but also in smaller machines such as Tore Supra and FTU. In JET LHCD has been used to produce electron barriers where the location of the barrier and the null shear region almost coincide and together move outwards in time [6]; moreover, in these reversed shear discharges a reduction of long wavelength (tens of cm) turbulence has been measured from the core out to the foot of the electron barrier [7]. In such wavelength range, the turbulence reduction is thought to be linked to ITG or TEM. In FTU barriers are obtained in electron-heated (LHCD+ECRH) discharges [8] with reversed q-profiles: here as well, the location of the barrier is consistent with the s=0 region. In Tore Supra electron ITBs in reversed shear discharges have been obtained both using LHCD and ICRH heating schemes [9]. Therefore, the s=0 condition and the associated reduction of turbulence seems to play an important role in a very large range of experimental conditions independently on the type of heating, machine size and injected power. To be done: still missing is an experiment with ion heating without injection of external momentum in order to evaluate the relative importance of rotation and magnetic shear in the barrier formation.

CONCLUSIONS

We have shown that ITBs are linked to ITG turbulence suppression by sheared E x B flow, but magnetic shear also plays a strong role in reducing the growth rate of the main instability. This is supported by the experimental observation that, when a barrier forms, the magnetic shear s at the radial location of the foot of the barrier is always very close to zero and the fact that a systematic coincidence of the $\omega_s > \gamma_m$ region with the location of a large variety of barriers, as deduced from the T_e and T_i profiles, can be obtained in several different discharges using for γ_m an expression with a linear dependence on $|s|$. The low magnetic shear (in particular the s=0 region) is therefore found to favour the barrier formation. This trend is also confirmed in electron heated discharges on JET as well as on other small tokamaks.

REFERENCES

[1]. E. Joffrin et al., submitted Nucl.Fus. (2001)

[2]. A. Rogister, Nucl.Fus. **41** 1101 (2001)

[3]. B. Esposito et al, 28th EPS Contr. Fusion and Plasma Phys., Madeira, (2001).

[4]. C. Challis et al., accepted Plasma Phys. Contr. Fus. (2002)

[5]. G. Tresset et al., Nucl.Fus. **42** 520 (2002)

[6]. G.M.D. Hogeweij et al., submitted Plasma. Phys. Contr. Fus. (2002)

[7]. G.D. Conway et al., submitted Plasma Phys. Contr. Fus. (2002)

[8]. C. Castaldo, these proceedings

[9]. G.T. Hoang et al, Phys. Rev. Lett. **84** 4593 (2000)

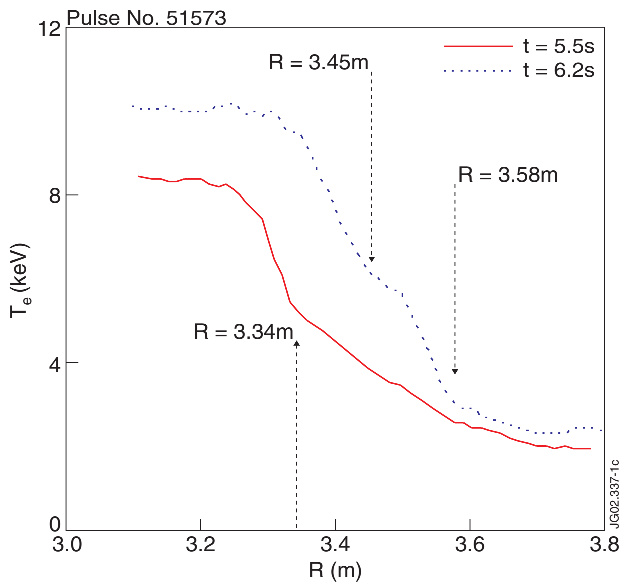

Figure 1(a): Discharge #51573: T_e profiles at t=5.5 s and t=6.2 s from KK3 electron cyclotron radiometer (arrows show barrier location).

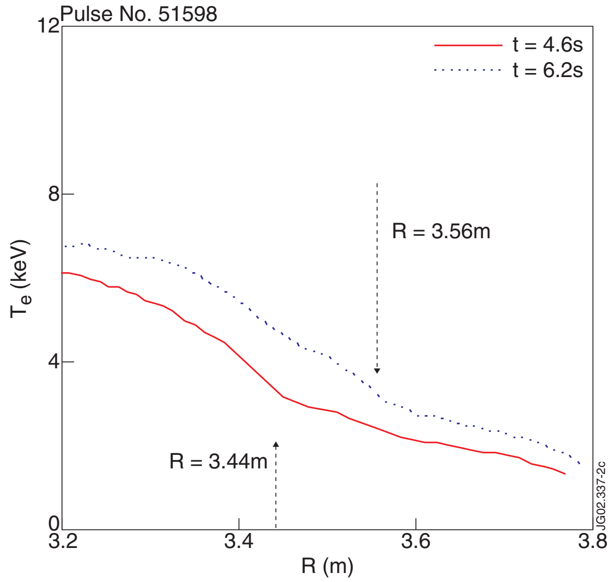

Figure 1(b): Discharge #51598: T_e profiles at t=4.6 s and t=6.2 s from KK3 electron cyclotron radiometer (arrows show barrier location).

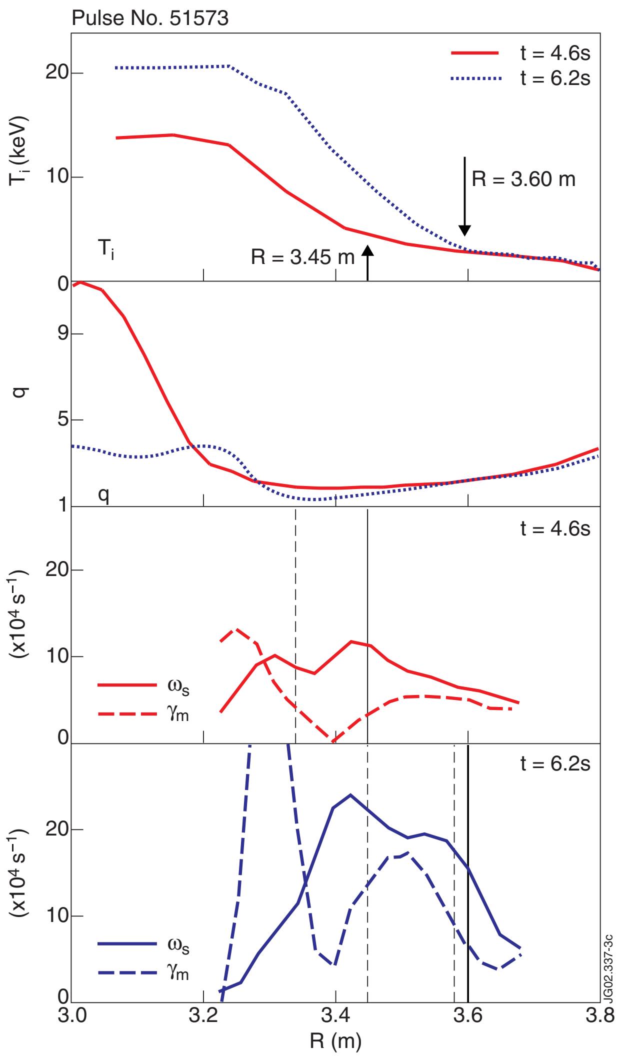

Figure 2(a): Discharge #51573: T_i, q profiles and $\omega_s > \gamma_m$ criterion.

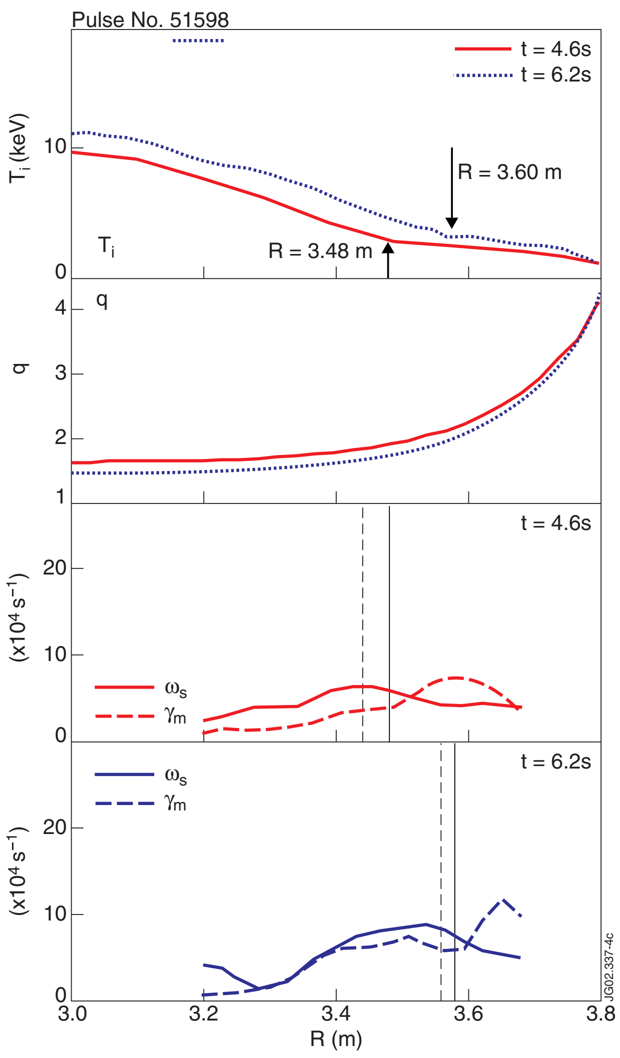

Figure 2(b): Discharge #51598: T_i, q profiles and $\omega_s > \gamma_m$ criterion.

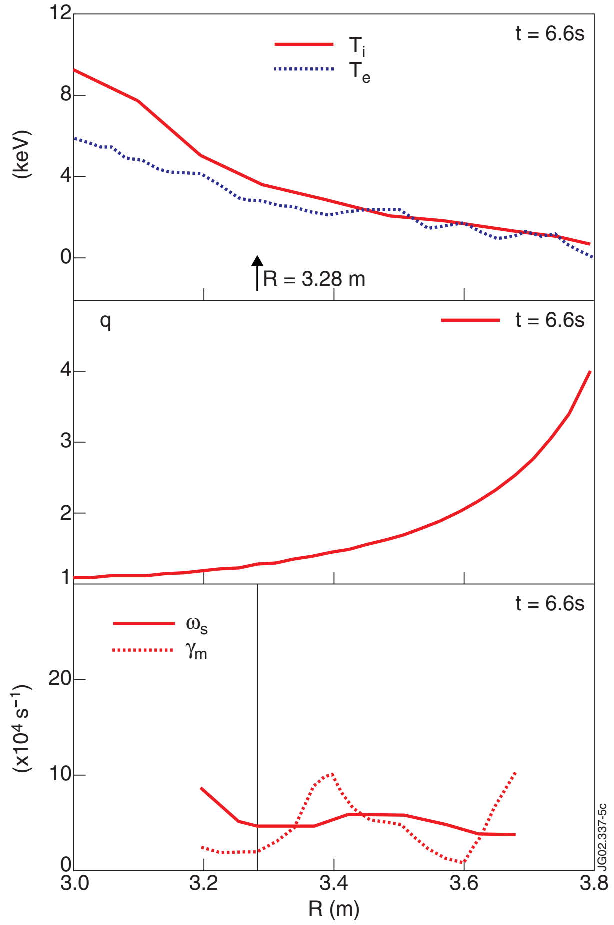

Figure 3: Discharge #51608: T_i,T_e (from LIDAR), q profiles and $\omega_s > \gamma_m$ criterion at t=6.6 s.

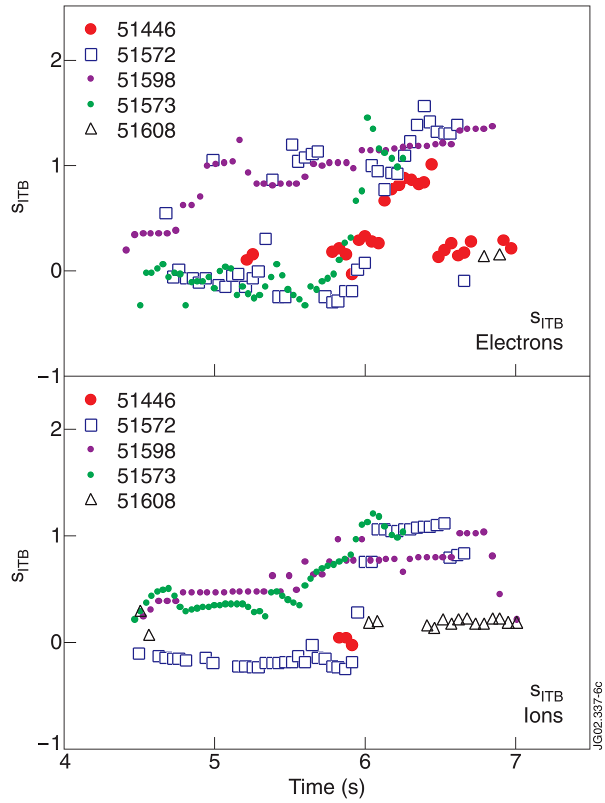

Figure 4: Time evolution of s_{ITB} taken from electron and ion temperature profiles in various discharges.