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ABSTRACT

Experimental observations and turbulence simulations have clearly identified the essential roles of local ExB shear, safety factor and magnetic shear, for triggering ITBs. Therefore, the amount of power required for ITB formation, so-called power threshold Pth depending on local plasma parameters, varies among different devices and additional heating methods. Previous analyses of the international ITB database [1, 2, 3], which has been compiled from experimental results of 9 tokamaks (AUG, DIII-D, FTU, JET, JT60, RTP, T10, TFTR, Tore Supra), have shown that the power threshold is a complex function of global parameters (Ip, B, a, n,...).

The main finding of this work is that the variation of P_{th} is strongly correlated with the normalized Larmor radius ρ* (ρ* = $\rho_{i\theta/a}$). P_{th} is found to be reduced by a factor of more than 2 for ρ* ≤5.10^{-3}. This feature is consistent with ITG theory and recent gyrokinetic simulations [4], which predict a transition from Bohm to gyro-Bohm when ρ* decreases. A favourable effect of negative/weak magnetic shear in reducing P_{th} is also reported. Finally, transport (with CRONOS code) and stability (with KINEZERO code) studies of a series of JET discharges with a systematic scan of ρ* are presented together with the global analysis.

INTRODUCTION

Advanced tokamak scenarios exhibiting the internal transport barriers (ITBs) has been extensively investigated in many tokamaks. Various conditions for the formation of ITBs are observed in different devices. The development of an international database is therefore important for clarifying the main physical mechanisms of the ITB formation and its sustainment. The present ITB database [1], which specially focuses on the necessary conditions to form ITBs, is being compiled from the experimental results of 9 tokamaks (ASDEX-U, DIII-D, FTU, JET, JT60, RTP, T10, TFTR, Tore Supra). It includes 126 0-D global and local parameters together with some 2-D quantities. The amount of injected power (P_{IN}) required for ITB formation is here found to depend on local plasma parameters, thus varying among different devices and additional heating methods. Previous analyses of the ITB 0D-datatabase [1-3] have confirmed that P_{IN} is indeed a complex function of global parameters (I_p, B_T, a, n,...). Many experimental observations and turbulence simulations have clearly identified the essential role played by the local ExB shear, safety factor (q) and magnetic shear (s), for triggering ITBs. This work consists in closely analyzing the pre-ITB phase, i.e. the moment when the barrier is formed, and is mostly relevant for ion ITBs. In particular, we concentrate on the influence of the confinement quality of the discharge and the magnetic shear in triggering an ion ITB.

1. INFLUENCE OF THE CONFINEMENT QUALITY ON THE ITB FORMATION

In Fig.1, the amount of injected power per particle is plotted versus the inverse of normalized gyroradius ρ* (ρ* being $\rho_{i\theta}/a$, and $\rho_{i\theta}$ calculated by taking the central ion temperature $T_i(0)$). We only select the pre-ITB phase for the negative magnetic (NS) shear configuration. Time derivative of the total stored energy dW/dt is less than 10% of P_{IN}, thus P_{IN} is approximately P_{loss}, defined as

$P_{loss} = P_{IN} – dW/dt$, for this data set. One can see that the injected power per particle is significantly decreases with 1/ρ*, and then saturates above 1/ρ* ~ 200. The same dependence is also seen in the RF electron heating discharges exhibiting electron ITBs only (Fig. 2). This indicates that the plasma targets which have a low ρ* value (e.g. 'good' confinement) are more favourable, since they require a low amount of P_{IN} for triggering ITBs. A possible explanation is that good confinement target conditions influence on E x B shearing rate γ_{ExB} (which is one of the crucial parameters for generating ITBs) by increasing the radial electric field through the pressure gradient or rotation,and/or increase α-stabilization effect. The result is consistent with the ITG theory and the recent gyrokinetic simulations in Ref [4] which predict a transition of transport characteristics from Bohm to gyro-Bohm when ρ* decreases

2. MAGNETIC SHEAR EFFECT ON THE ITB FORMATION

The effect of magnetic shear can be seen in Fig.3, in which we report on discharges having different q-profiles (positive magnetic shear (PS), weak shear (WS) and NS). One can see that NS and WS plasma targets are much more favourable for ITB formation, with P_{IN} being significantly reduced. At 1/ρ* = 100-150, P_{IN} required for the ITB formation in PS plasmas is 2-3 times higher than that in NS and WS configurations. This is consistent with some low power ITB experiments exhibiting a hollow q-profile (FTU, RTP, Tore Supra), particularly the results of optimized shear experiments at JET in which P_{IN} was significantly reduced by preforming a hollow q-profile using lower hybrid current drive (LHCD) [5]. Clear example of JET discharges was carefully analyzed in Ref [6]. It consists in comparing two JET discharges characterized by the same target parameters, but completely different q-profiles at the pre-ITB phase. As shown in Fig.4, both the discharges were performed at I_p = 2.2MA / B_T =2.6T; LHCD was applied very early in the first one (No: 51613) in order to preform a nonmonotonic q-profile (Fig.5). In reversed shear discharge No: 51613, one can see the formation of both the electron and ion ITBs at t = 5.7s, during NBI and ICRH applications (T_e and neutron rate signals). Contrarily, no transition was observed in monotonic q discharge (No: 51611), although the same amount of NBI and ICRH powers was applied. Stability analyses of these discharges have been performed [7] using a linear electrostatic gyro-kinetic code [8]. At t = 5.7s, just before the ITB formation, the TEM and ETG microinstabilities were found to be stabilized (Fig.6). Furthermore, the linear growth rate of ITG branch was significantly reduced. Radial profiles of maximum linear growth rate γ_{lin}^{max} (Fig.7(a), corresponding mostly to ITG mode (low wave number, $k_\theta \rho_i < 1$), display a strong reduction of γ_{lin}^{max} inside the barrier, linked to negative magnetic shear. The shaded uncertainty regions on γ_{lin}^{max} correspond to the error bars of the temperature and density gradients. The magnetic shear effect in decreasing •γ_{lin}^{max} was also found in [8-9]. Note that $\gamma_{E \times B}$ could account for turbulence reduction. However, the very marginal differences in its radial profiles within the error bars (Fig.7(b) cannot explain the wide barrier in Pulse No: 51613. Thus, the comparison of these two discharges clearly demonstrates that it is possible to trigger an ITB by producing a non-monotonic q-profile without increasing the ExB flow shear.

3. ESTIMATION OF THE POWER REQUIRED FOR THE NEXT STEP DEVICES USING A SIMILARITY APPROACH

Similarity analysis is performed using the relationship between P_{loss} and the dimensionless parameters ρ^* , υ., β: P_{loss} (a/R) $a^{3/4}$ = F(υ^*, β) $(\rho^*)^{\alpha-5/2}$ (Eq.1) This expression is obtained from the following formulas for the heat diffusivity (χ) and the energy confinement time (τ_E): $\chi \propto (\rho^*)^{\alpha}$ F(υ^*, β) T/B ; $\tau_E \propto a^2 / \chi$ and $\tau_E \propto$ n T a^2 R / P_{loss}. The power coefficient α is equal to 5/2 or 3/2, depending on the transport property which is either Bohm or gyro-Bohm. Thus, the plot of the normalized power P_{loss} (a/R) a3/4 versus 1/ρ^*, in keeping β and υ^* constant, illustrates the confinement quality of the discharge. In Fig.8, Ploss (a/R) a3/4 is plotted as a function of 1/ρ^*. The case β = 1 seems to indicate a weak dependence on υ^* within the uncertainties of measurements, since it corresponds to two quite different values of υ^* (0.03 and 0.23). Best power fit, for both cases β = 1 and β = 3, gives a value of the power coefficient α (in Eq.1) between 1.5 and 1.75 which suggest that the ion transport is likely gyro-Bohm in NS case. A reasonable extrapolation indicates that ITBs could be triggered with a moderate injected power in a next step machine by producing a hollow q-profile. In ITER: T_i =8keV and ρ^*(at a/2) = 3.510^{-3}, we could expect an ion ITB formation with about 40 MW of injected power (case β / υ^* =3/0.03 in Fig.8).

SUMMARY

The main finding of the present work is that the injected power required for triggering ion ITB can be significantly reduced by controlling the magnetic shear without increasing the ExB flow shear. Good confinement target plasmas are also found to be favourable for decreasing the power required to produce an ITB.

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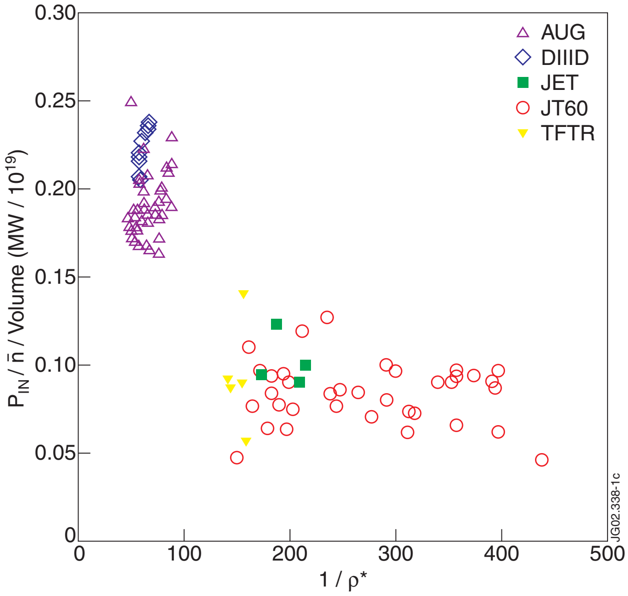

Figure 1: Injected power per particle as a function of 1/ρ in the ion pre-ITB phase for NS configuration.*

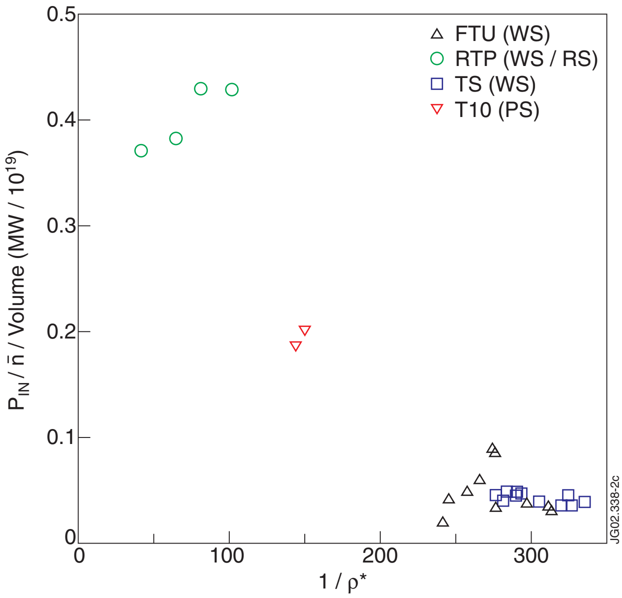

Figure 2: Injected power per particle as a function of 1/ρ in the electron pre-ITB phase for NS configuration*

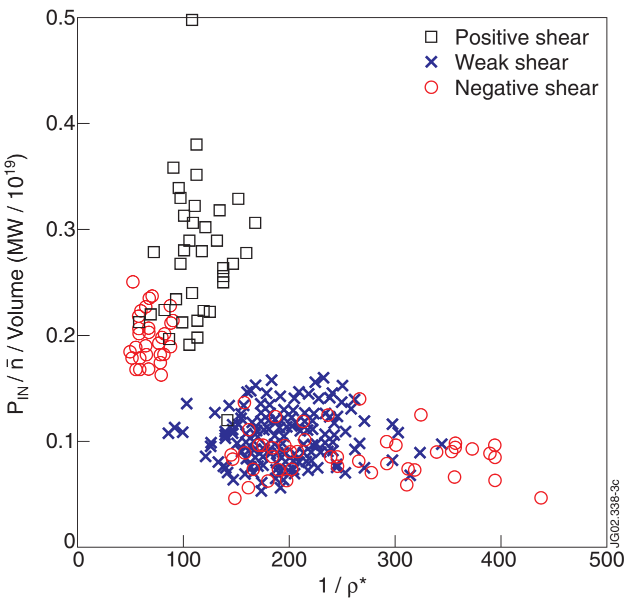

Figure 3: Injected power per particle as a function of 1/ρ, taken at the ion pre-ITB phase, for various qprofiles in ASDEX-U, DIII-D, JET, JT60-U and TFTR (PS data from JT60-U only).*

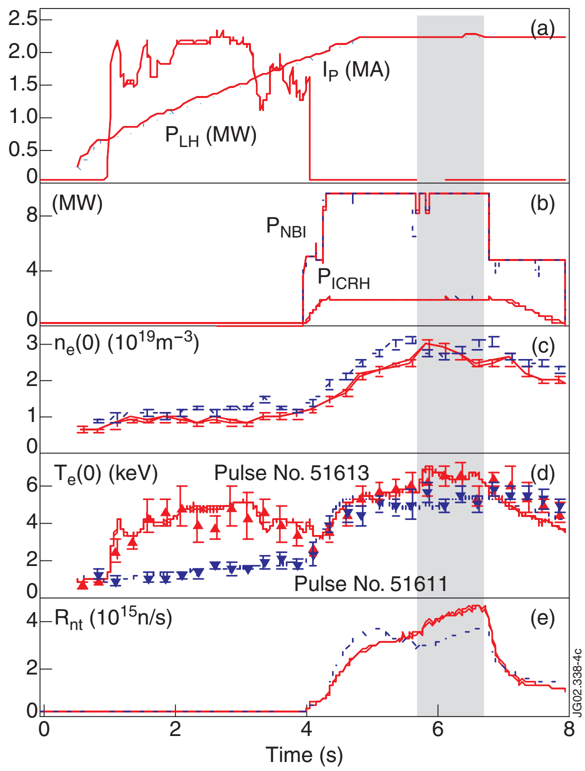

Figure 4: Comparison of two JET discharges with (No:51613, solid) and w/o (No:51611, dashed) LHCD: (a) Plasma current and LH power; (b) NBI and ICRF power; (c) electron density; (d) electron temperature; (e) neutron rate.

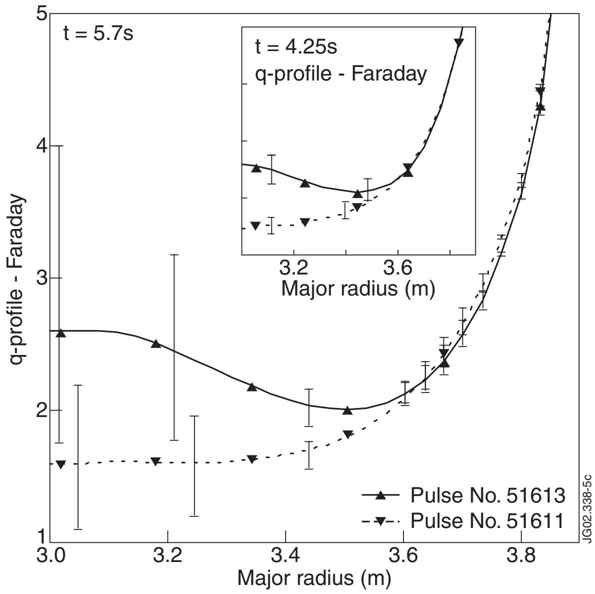

Figure 5: Safety factor profile obtained from equilibrium reconstruction constrained by Faraday (at t = 5.7s) and MSE (at t = 4.25s) measurements.

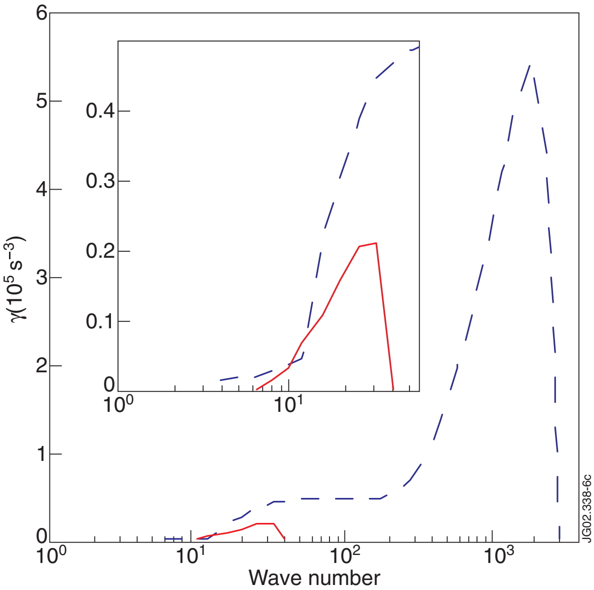

Figure 6: Growth rate for NS (solid) and PO (dashed) discharges in Fig. 4, computed at t=5.7s and at around mid radius.

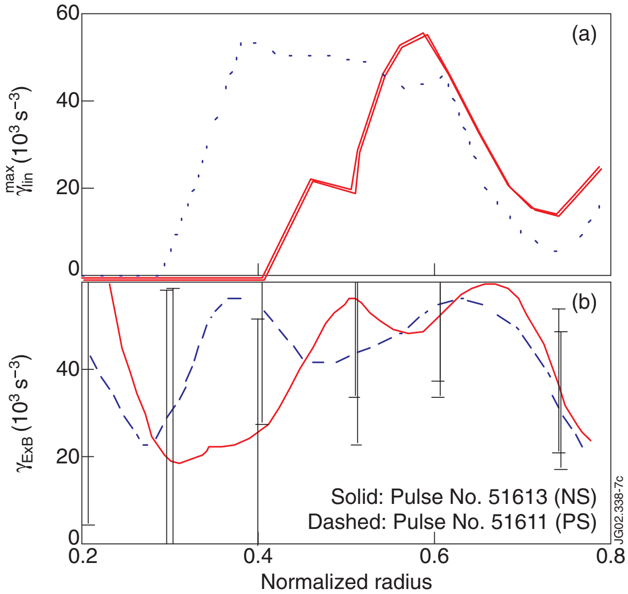

Figure 7: Radial profiles of $\gamma_{\text{lin}}^{\text{max}}$ ($k_\theta \rho_i < 1$) and γ_{ExB} at the pre-ITB phase (t=5.7s)

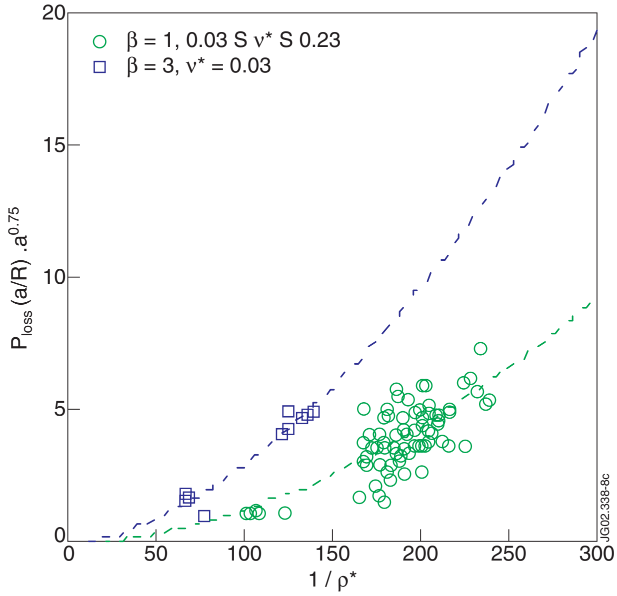

Figure 8: Similarity approach for the ion pre-ITB phase in NS configuration