32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.29C, P-2.028 (2005)

Ion ITB dynamics in ASDEX Upgrade

G. Tardini[1], J. Hobirk[1], C. Ludescher[2], C. F. Maggi[1], P. Martin[1], D. McCune[2], A. G. Peeters[1], A. C. C. Sips[1], A. Stäbler[1], J. Stober[1], and the ASDEX Upgrade Team[1]

[1]*MPI für Plasmaphysik, Euratom Association, Boltzmannstr. 2, 85748 Garching, Germany*
[2]*Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ08543, USA*

1 Introduction

Internal Transport Barriers (ITBs) are characterised by high energy confinement and bootstrap current fraction, which makes them a candidate scenario for steady state tokamak operation. However, a steady-state ITB scenario suitable for reactor parameters has not yet been reached, especially at high plasma density (n_e). In ASDEX Upgrade ion temperature (T_i) ITBs exhibit particularly good confinement. Their lifetime is, however, limited to a few energy confinement times (τ_E's), which raises concerns for steady state operation. In this paper we show that ITBs collapse before the first type-I Edge Localised Mode (ELM) burst occurs. Transport simulations highlight the role of thermal ions' dilution in the ITB formation. Gyrokinetic linear stability analysis yields a threshold for the fast ions fraction to suppress anomalous transport. The concentration of fast ions from Neutral Beam Injection (NBI) is predicted time-dependently and compared to the gyrokinetic threshold.

2 ITB performance and timing

Ion ITBs at ASDEX Upgrade are obtained typically by applying strong NBI heating (usually 10 MW) in one step with low n_e, between 1 and 2 10^{19} m^{-3} at NBI onset time. Despite varying plasma current, magnetic field and NBI timing with respect to the current flat top, the ITB performance and timing do not change significantly, although different MHD activity is observed [2].

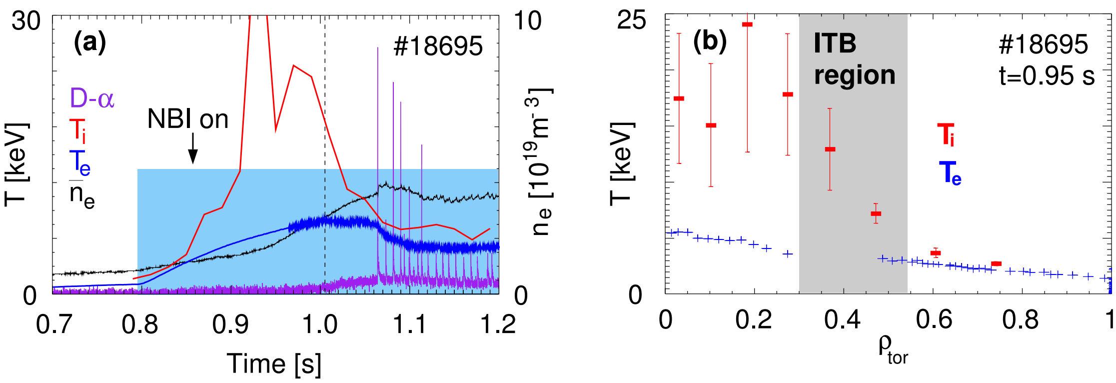

Figure 1. Discharge #18695. (a) T_i (red) and T_e (blue) at $\rho_{tor} \sim 0.2$, line averaged n_e (black), D-α divertor signal (violet). The dashed line marks the beginning of the ITB loss. (b) T_i and T_e profiles during the ITB phase.

Fig. 1 shows the time evolution of a typical ASDEX Upgrade ITB discharge. The T_i time trace provides evidence that a barrier forms some 70-100 ms after the beams are switched on and eventually collapses 100-150 ms later. For comparison, $\tau_E \approx 150$ ms in the ITB phase. The performance and the reproducibility of the scenario are discussed in [2]. The major drawback is its short lifetime, of the order of the beam slowing down time (τ_{sd}), about 100 ms in the core plasma during the ITB phase, which is comparable to τ_E. ELMs are commonly believed to be a major candidate for the loss of the good energy confinement phase, as observed in JET [3]. Fast measurements of core T_i with the Charge eXchange Recombination Spectroscopy (CXRS) resolve the ITB loss with respect to the ELMs onset. In most cases ion ITBs in ASDEX Upgrades are observed to collapse already before the first ELM burst occurs, as shown in Fig. 2.

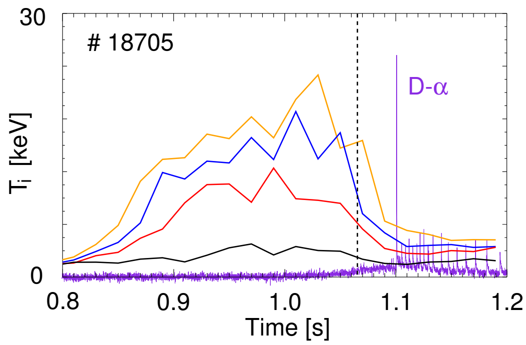

Figure 2. Core T_i measurements from CXRS and ELM timing from D-α divertor signal (violet). Different colours of the T_i traces correspond to different lines of sight. The dashed line marks the beginning of the ITB loss.

Therefore, in general ELMs are not the cause of the confinement degradation, although it is not ruled out that in some cases they might terminate the ITBs.

3 Fast ions and ITBs

Ion heat transport in H-mode discharges has been found to be dominated by the Ion Temperature Gradient (ITG) driven mode [4]. In order to obtain an ion ITB, the ITG mode must be locally suppressed. A statistical study of transport barriers' onset criteria at ASDEX Upgrade identifies n_e as the key parameter for ITB formation [5]. No significant off-axis current is driven, as mostly central NBI sources are used. No pre-heating is applied either. Therefore, the magnetic shear is not strongly negative, so it cannot account alone for the linear stability of the ITG mode.

Fluid transport models predict the ITB intensity, location, width and duration in good agreement with the experiment. The mechanism for transport suppression is found to be thermal ions dilution by the injected fast beam ions [2]. A quantitative study of the fast ions fraction n_{fast}/n_e required to stabilise the ITG mode is performed with the gyrokinetic code GS2 [6]. At the ITB onset conditions, the ITG growth rate decreases with increasing n_{fast}/n_e. Assuming $\omega_{E\times B} = 0.1 v_{th}/R$ and the stability criterium $\omega_{E\times B} > \gamma_{ITG}$ [7], the ITG mode is stabilised for n_{fast}/n_e ¿ 30-35 %. Once the barrier is established, the higher ∇T_i makes the ITG mode more unstable, but both $\omega_{E\times B}$ and the Shafranov shift are larger, due to increased v_{tor} and plasma pressure, respectively. A crucial stabilising role is, however, played by the ratio T_i/T_e, which can be as high as 5 during the ITB phase. Fig. 3 (b) shows a scan of n_{fast}/n_e with plasma parameters from the ITB phase. Full points refer to the case with $T_i/T_e = 2$, empty symbols to $T_i/T_e = 2.5$, while all other parameters are kept unchanged. This suggests a possible mechanism for the ITB collapse. In fact, any increase of ion heat transport reduces T_i/T_e, $\omega_{E\times B}$ and the Shafranov shift, thus making the ITG mode more unstable. In this way, a runaway confinement loss can occur until $\nabla T_i/T_i$ is low enough not to destabilise the mode further. The GS2 calculations summarised in Fig. 3 find a continous reduction of the ITG growth rate even when it is unstable. A moderate improvement of ion heat transport by thermal ions dilution can therefore be expected also after the ITB phase is terminated and in general for low density plasmas with significant NBI.

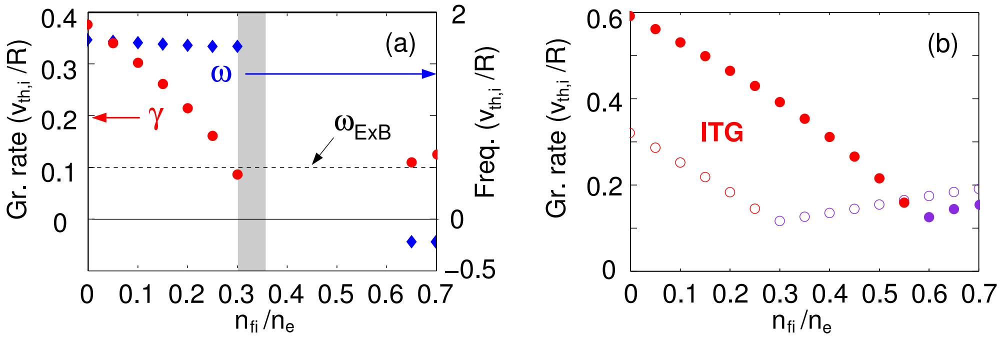

Figure 3. GS2 scan of n_{fast}/n_e. (a) At ITB onset: r/a=0.3, $\hat{s}$=0.5, $\alpha = 0.01$, $T_i = 7$ keV, T_e = 3.5 keV, $T_{fast} = 70$ keV, R/L_{T_i}=10, R/L_{T_e}=6, R/$L_{T_{fast}}$=0.5, R/L_{n_e}=4. (b) During the ITB phase: R/L_{T_i}=15, R/L_{T_e}=7, other parameters as in (a). Full points refer to $T_i/T_e = 2$, empty symbols to $T_i/T_e = 2.5$. For violet points the ITG is not the leading mode.

An accurate, time-dependent NBI modelling is required for a quantitative assessment on the local fast ion population. In this way we can judge the relevance of the mechanism suggested for ITB formation and eventual collapse. This is now possible since the TRANSP code has been succesfully implemented at ASDEX Upgrade, in particular the NBI module NUBEAM [8]. The other NBI codes available for ASDEX Upgrade so far assume steady state.

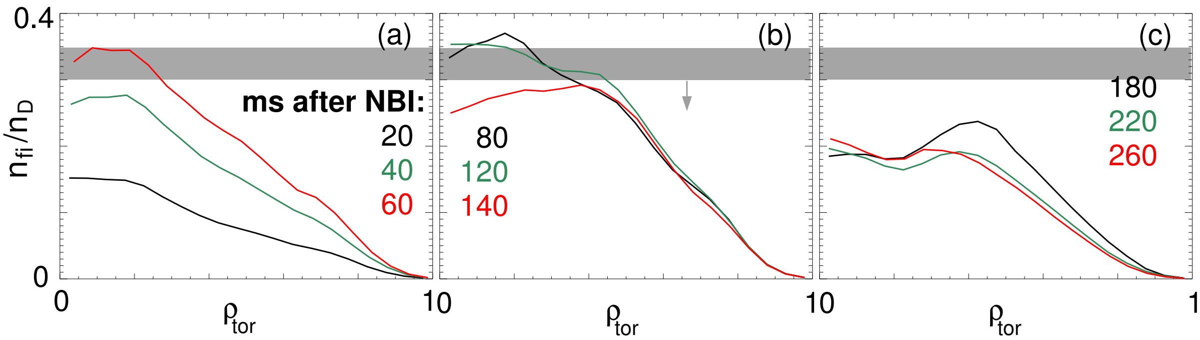

Figure 4. Time evolution of the fast ions fraction profile as predicted by TRANSP for discharge # 18695 (same as in Fig 1). (a) Before the ITB. (b) During the ITB. (c) After the ITB. The shaded region corresponds to the ITG threshold predicted by GS2.

While our GS2 calculations neglect impurities to reduce the computing time, TRANSP calculations retain realistic Z_{eff} values in order to obtain a more accurate description of the beam slowing down. Since impurities further dilute the thermal main ions, it is more appropriate to compare n_{fast}/n_D, n_D being the total deuterium density $n_{fast} + n_{D,th}$, rather than n_{fast}/n_e which is in principle the relevant quantity for the ITG mode. The fast ion fraction profiles are plotted in Fig. 4. The plasma parameters and profiles are taken from the experiment, while the equilibrium is computed by the internal equilibrium solver. As Fig. 4 (a) shows, the fast ion population accumulates during the slowing down process. Then the amount of fast ions hardly changes. However, the beam fuelling enhances the background n_D, so that the fraction of fast ions decreases in time. Moreover, as n_D increases, the beams penetrate less and τ_{sd} becomes shorter, thus reducing further the ratio n_{fast}/n_D. Fig. 4 (b) and (c) illustrate this behaviour quantitatively. In particular, the concentration of fast ions predicted by TRANSP is well consistent with the ITB formation mechanism proposed in [2]. The threshold predicted by gyrokinetic theory (shaded region in Fig. 4) is matched locally by the TRANSP fast ions profile. The timing is in good agreement with the experiment as well as the ITB location, which can extend up to $\rho_{tor} \approx 0.30 - 0.40$. Note that the uncertainty in the measured n_e profile affects the accuracy of the NBI reconstruction by enhancing the denominator of the ratio n_{fast}/n_D and by reducing the beam penetration and τ_{sd}. Nevertheless, after $\sim 2\tau_{sd}$ the fast ions fraction is by far too low to sustain an ITB, reinforcing the explanation of the ITB collapse mechanism presented above.

4 Discussion

The time dependent simulation of the fast ion content with TRANSP confirms that the thermal ions are diluted enough to prevent the ITG mode to develop in the central plasma region, up to $\rho_{tor} \approx 0.30 - 0.40$. The onset time of the transport barrier is explained, too. This explains the density threshold for ASDEX Upgrade ion ITB formation, discussed in [5]. Its lifetime is also consistent with the mechanism proposed, due to the increase of the background plasma density on a τ_{sd} time scale. According to the ITB physics presented in this paper, the ITB collapse can neither be prevented nor significantly delayed, since the ITB must be sustained by a high amount of fast particles which are delivered by NBI. In fact, beam particles fuel the plasma, thus increasing the background n_e and leading to the ITB collapse as discussed above. Ion Cyclotron Resonance Heating (ICRH) delivers fast ions and almost no particle fuelling, but the amount of fast ions is negligible compared to the background n_e, therefore ICRH is not suited to replace (even partly) NBI sources for ITB formation. Additionally, in order to obtain enough bootstrap current the ITB should be broader. However, the required fast ion densities were never reached outside $\rho_{tor} \approx 0.35$ so that this scenario is not promising for non-inductive operation.

In particular this scheme of turbulence suppression is expected to be inefficient in ITER. In fact, high voltage negative ion sources yield good beam penetration. However, given the high energy per injected ion, for the same NBI power much less fast particles are injected. Additionally, the large device size prevents the local accumulation of suprathermal ions. Fusion α-particles contribute to thermal ions dilution too, but the fraction of n_α/n_e planned for ITER-FEAT ranges between 0.001 and 0.008 [9], which is more than one order of magnitude too low for the ITB onset mechanism described in this paper.

References

[1] A.G. Peeters *et al*, 18th IAEA Fusion Energy Conf. (2000) IAEA-CN-77/EXP5/06
[2] G. Tardini *et al*, 31st EPS Conference, London 2004, Paper P4.123
[3] A.C.C. Sips *et al*, Nuclear Fusion **41** (2001) 1559
[4] G. Tardini *et al*, Nuclear Fusion **42** (2002) 258
[5] E. D. Quigley *et al.*, Nuclear Fusion **44** (2004) 1189
[6] M. Kotschenreuther *et al*, Physics of Plasmas **2** (1995) 2381
[7] T. S. Hahm, K. H. Burrell, Physics of Plasmas **2** (1995) 1648
[8] A. Pankin, D. McCune, R. Andre et al., Comp. Phys. Comm. **159**, No. 3 (2004) 157
[9] ITER Physics Basis, Nuclear Fusion **39** (1999) 2137