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ITB Collapse and ELMs in ASDEX Upgrade

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1 Introduction

An Internal Transport Barrier (ITB) is a region in the core plasma with unusually steep temperature (or density) gradient. High bootstrap current fraction and enhanced energy confinement make ITBs an attractive scenario for a steady-state tokamak reactor. However, steady-state ITBs in reactor-like conditions have still to be demonstrated.

On ASDEX Upgrade well reproducible ion temperature (T_i) ITBs are generated with Neutral Beam Injection (NBI) heating, yielding central T_i values up to 25-30 keV [1]. The drawback is their duration of only several energy confinement times (τ_E's). Since type I Edge Localised Modes (ELMs) have been observed to terminate the ITB phase [2], we aim to obtain a longer ELM-free phase in order to study the correlation with the barrier collapse, as described in Section 2. Transport simulations are presented in Section 3, improving our understanding of the ITB dynamics.

2 Experimental results

Ion temperature and toroidal velocity (v_{tor}) are measured with the Charge eXchange Recombination Spectroscopy (CXRS) diagnostics. Since 2004 a fast CXRS system is operating. Time resolution of 20 ms has been used.

The ELMs delay is attempted with low plasma current (I_{pl}), following the results [3]. Alternatively, impurity puffing induces significant radiation, mitigating the ELM activity. In all discharges, the plasma density (n_e) is kept as low as possible and the NBI power (P_{NBI}) is 10 MW, with all sources switched on simultaneously. Only # 18513 has 7.5 MW instead. Although magnetic field, I_{pl}, radiated power and NBI timing have been varied, all ITBs exhibit a similar time evolution, shown in Fig. 1. The ITB develops about 70 ms after the beams are injected. It reaches its maximum performance in terms of $T_i(core)/T_i(edge)$ some 100 ms later, eventually decaying after 50-150 ms. At this time the plasma energy stops growing and the D-α signal increases. The loss in T_i is temporarily compensated by n_e fuelling, so the plasma energy keeps roughly constant (Fig. 1). The electron temperature T_e has also a plateau before dropping with the first ELM burst. Typical T_i, T_e and v_{tor} profiles during the ITB phase are shown in Fig. 2. For the time evolution of T_i, see Fig. 5 (points). The ITB decay occurs on a τ_E scale ($\sim$ 100 ms).

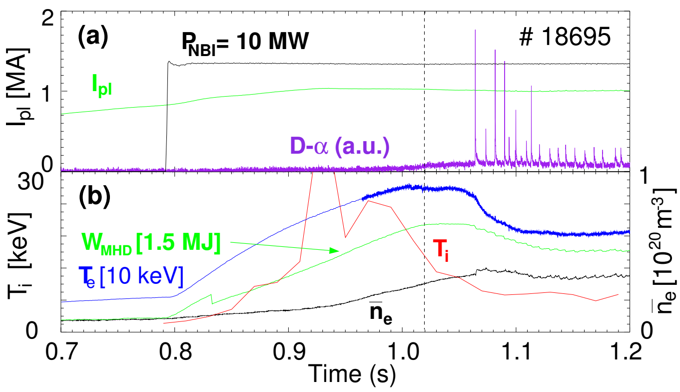

Figure 1. Time traces of #18695. (a) I_{pl}, P_{NBI} and D-α divertor signal. (b) T_i and T_e at $\rho \sim 0.2$, line averaged n_e from interferometry, total plasma energy.

The dashed line marks the beginning of the ITB loss. At maximum stored energy, q95=5.8, β_{pol}=1.6, β_N=2.2, H89=2.9.

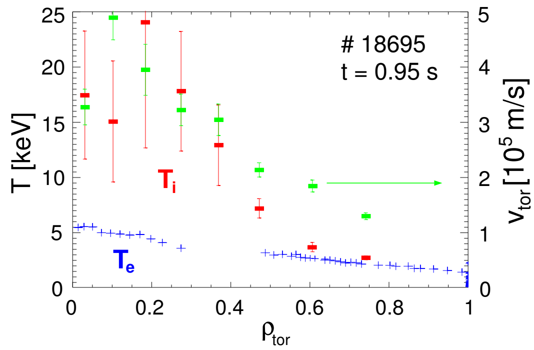

Figure 2. T_i, T_e and v_{tor} profiles during the ITB phase. $T_i/T_e > 3$ in the plasma core. While v_{tor} is overall steep, no localised strong gradient is observed.

ITBs have been observed to be gradually eroded by ELMs [2]. Also in ASDEX Upgrade's # 18513, with only 7.5 MW NBI, the ITB survives the first ELM events, but is weaker than the others presented here as the central T_i does not exceed 15 keV. On the other hand, in most ITB discharges of the present database the collapse occurs already before the first type I ELM (Fig. 3 (a)). The plasma energy plateau is associated with a decrease (or at least a plateau) of T_e. Simultaneously, the neutrons' rate begins to drop (Fig. 3 (b)) and in several cases dn_e/dt steepens. The D-α signal increases too. These experiments show that, although ELMs can lead to a collapse of the barrier, the ITB is lost also without any ELM activity. In fact, the confinement loss starts before the ELMs and continues across the first bursts (Fig. 3). It is possible that the discharge goes into H-mode when the ITB decays, even before the ELMs. Also discharge # 17905, with T_i measurements from the old CXRS system (time resolution: 70 ms), shows a clear ITB loss at 1 s, much before the first ELM occurs at 1.13 s. Then, in all discharges type I ELMs follow immediately with decreasing amplitude.

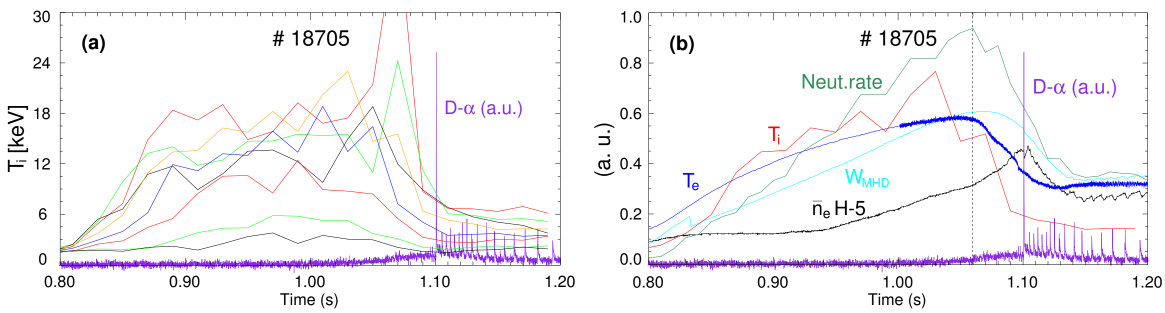

Figure 3. (a) T_i time traces from CXRS and ELM timing. (b) Time traces related to the ITB loss: T_i (red), T_e (blue), line averaged n_e (black), neutrons emission rate (green), MHD energy (cyan), D-α signal (violet). The dashed line marks the beginning of the ITB loss.

Core MHD activity, limiting the energy confinement, differs from discharge to discharge. Also within the same discharge it varies strongly in time due to the rapidly increasing n_e. In several discharges the current ramp-up was performed in two time steps. Interestingly, they feature fishbones (Fig. 4). This is an evidence for a significant amount of fast ions. At the same time, the fishbone instability expels fast ions from the plasma. Such discharges exhibit the longest-lived ITBs of the present database. Strong MHD activity, usually (2,1) or (3,1), is observed together with the beginning of the energy confinement loss and increased D-α signal. (Figures 1 and 4 at t $\sim$ 1.02 s). Unfortunately, measurements of the safety factor profile were not available for these discharges.

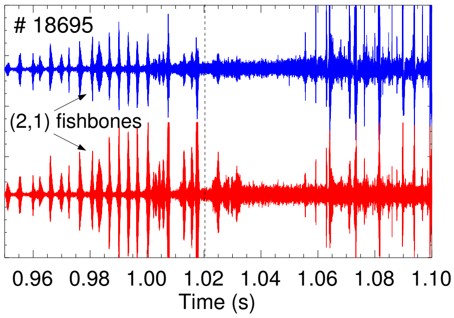

Figure 4. Core MHD activity in the ITB discharge # 18695. In the early phase, (2,1) fishbones are observed. Later, several MHD modes are active, as the plasma energy saturates (dashed line as in Fig. 1) and eventually drops.

3 Transport modelling and linear stability analysis

Theory-based 1D fluid models are selected for time-dependent simulation of the ITB discharges in the ELM-free phase: the Weiland [4] and the renormalised GLF23 [5] models. Both models are based on Ion Temperature Gradient (ITG) and Trapped Electron Mode (TEM) physics, differing mainly for the fluid closure. A dilution approximation is assumed for impurities and for NBI fast ions. The models are implemented in the ASTRA code [6] and return particle and heat transport coefficients. Transport reduction by plasma rotational shear ($\omega_{E\times B}$) is imposed according to the default implementations of the authors using the experimental v_{tor} and the neoclassical v_{pol} profiles. The NBI deposition profiles are computed with the standard ASTRA package, which is time independent and neglects finite slowing down time (τ_{sd}). The injected fast particles are assumed to be a small perturbation of n_i. TRANSP simulations are required for more reliable reconstructions of the particle deposition and current drive profiles. The boundary conditions for the T_i, T_e and n_e profiles are the time dependent experimental values at $\rho_{tor} = 0.8$. Current diffusion is computed too. Core MHD is not modelled.

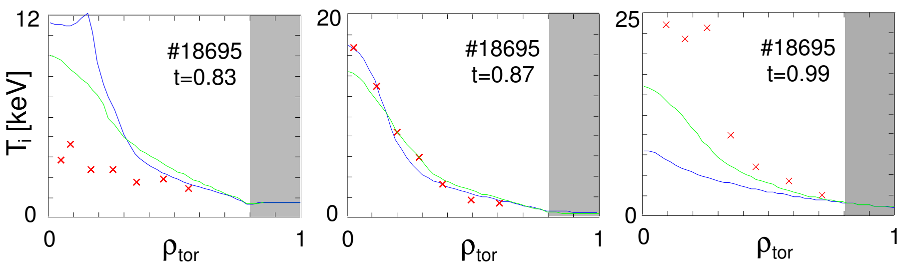

Figure 5. T_i profile from the experiment (points), Weiland (blue) and GLF23 (green) models. NBI heating from 0.8 s.

As Fig. 5 shows, both models yield a good agreement with the experiment at t=0.87 s, predicting the ITB's location, width and gradient length L_{T_i}, where for a given profile f it is $L_f = f/|\nabla f|$. The ITB duration of the order of τ_E is qualitatively reproduced, although in the Weiland model the collapse takes place earlier. The experimental ITB forms 70 ms after the NBI is switched on, i. e. within τ_{sd}. In fact, the injected fast ions accumulate until they get thermalized on a τ_{sd} time scale; then, their amount keeps roughly constant. In the simulation, transport is damped immediately after the NBI-switch on, as finite τ_{sd} is neglected. Hence, the ITB forms already within 30 ms (Fig. 5). A detailed investigation points out that in the modelling the key parameter for ITG suppression is the local fast ions density n_{fast}. Indeed, fast ions injected via NBI are not resonant for the ITG mode, due to their much higher drift frequency. If n_{fast} is a significant fraction of the background ions, thermal ions are too diluted to develop the ITG instability loop. Within this picture, a n_e threshold for ITB formation at given P_{NBI} is predicted, in agreement with ASDEX Upgrade results [7]. A rough global estimate under the experimental conditions yields $n_{fast}/n_e \approx 0.5$, neglecting charge exchange with background neutrals. dn_e/dt measured with the Thomson scattering diagnostics yields a value of $n_{fast}/n_e \approx 0.3$. Typically, the n_{fast} profile is more peaked than the background density, so in the inner region the fraction is expected to be higher.

Linear stability analysis provides a check of the fluid models' predictions by means of the more comprehensive gyrokinetic theory. The GS2 code [8] is used with plasma parameters at ITB onset: T_i =7 keV, T_e =3.5 keV, T_{fast} =70 keV, $\epsilon = 0.1$ (corresponding to $r/a \approx 0.3$), $q = 2$, $\hat{s} = 0.5$, $\alpha = 0.01$, $R/L_{n_e} = 4$, $R/L_{T_e} = 6$, $R/L_{T_i} = 10$, $R/L_{T_{fast}} = 0.5$, zero collisionality. R is the tokamak major radius, α the Shafranov shift, $\hat{s}$ the magnetic shear. n_{fast}/n_e is scanned preserving quasi-neutrality: the results are summarised in Fig. 6. A threshold at $n_{fast}/n_e \approx 0.35$ is observed, after which the ITG is damped. $\omega_{E\times B}$, not considered in GS2 calculations, downshifts this threshold. A dependence on T_i/T_e is observed: for high T_i/T_e less fast ions are needed to sustain the ITB. So while n_{fast}/n_e is crucial for the formation of these ASDEX Upgrade barriers, it could be less determinant for their sustainment. Both n_{fast}/n_e as well as T_i/T_e decrease with increasing background n_e, which cannot be avoided due to NBI particles thermalization.

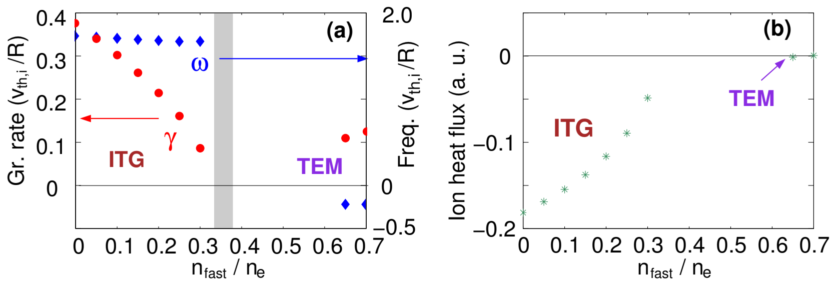

Figure 6. GS2 scan of fast ions fraction. Above $n_{fast}/n_e \approx 0.35$ the ITG mode is stabilised. $\omega_{E\times B}$, not retained in GS2, downshifts the threshold.

4 Conclusions

Reproducible ITBs are done on ASDEX Upgrade with 10 MW pure NBI heating. While type I-ELMs cannot be avoided, not even at low I_{pl} nor using radiation by impurities, the ELM-free phase is long enough to study the ITB evolution. Fast CXRS measurements show that usually a clear ITB loss occurs before the first ELM.

Transport analysis highlights n_{fast}/n_e as the key parameter triggering the ITB. For the sustainment, T_i/T_e plays an important role as well. $\omega_{E\times B}$ completes the ITG mode stabilisation when the growth rate is reduced by the fast particles. The proposed mechanism can explain the density threshold for ITB formation and possibly the ITB duration which is of the order of the slowing down time. A more careful assessment of the non-thermal ion population is necessary, however, to come to definitive conclusions.

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