

## ITB Collapse and ELMs in ASDEX Upgrade

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### 1 Introduction

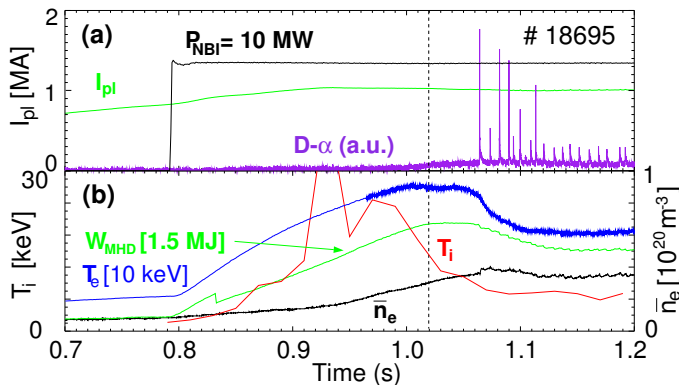
An Internal Transport Barrier (ITB) is a region in the core plasma with unusually steep temperature (or density) gradient. High bootstrap current fraction and enhanced energy confinement make ITBs an attractive scenario for a steady-state tokamak reactor. However, steady-state ITBs in reactor-like conditions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

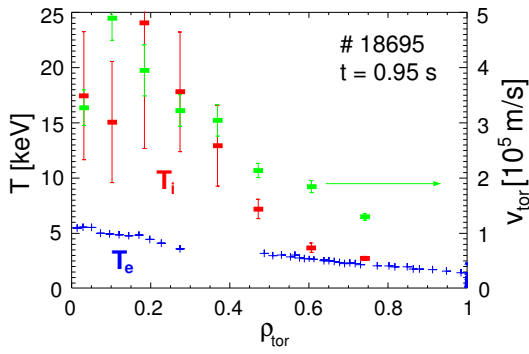
The ELMs delay is attempted with low plasma current ( $I_{pl}$ ), following the results [3]. Alternatively, impurity puffing induces significant radiation, mitigating the ELM activity. In all discharges, the plasma density ( $n_e$ ) is kept as low as possible and the NBI power ( $P_{NBI}$ ) is 10 MW, 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- $\alpha$  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  $\tau_E$  scale ( $\sim 100$  ms).



**Figure 1.** Time traces of #18695.

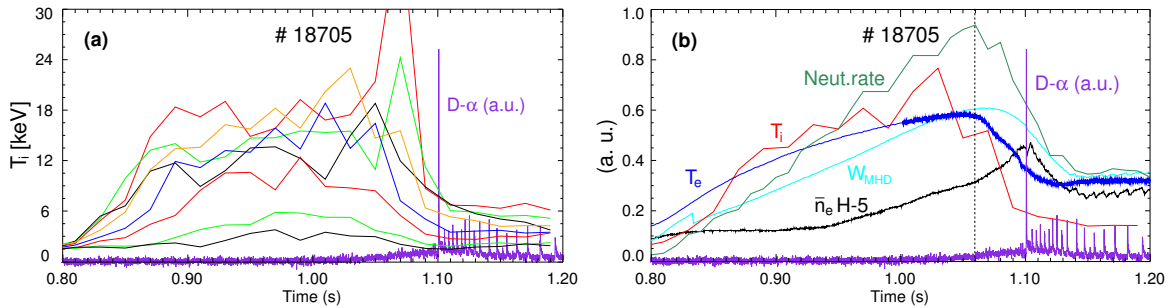
(a)  $I_{pl}$ ,  $P_{NBI}$  and D- $\alpha$  divertor signal. (b)  $T_i$  and  $T_e$  at  $\rho \sim 0.2$ , line averaged  $n_e$  from interferometry, total plasma energy.

The dashed line marks the beginning of the ITB loss. At maximum stored energy,  $q_{95}=5.8$ ,  $\beta_{pol}=1.6$ ,  $\beta_N=2.2$ , 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- $\alpha$  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.



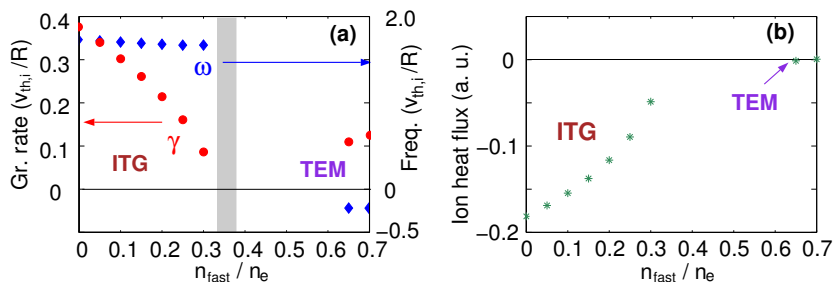
**Figure 3.** (a)  $T_i$  time traces from CXRS and ELM timing. (b) Time traces related to the ITB loss:  $T_i$  (red),  $T_e$  (blue), line averaged  $n_e$  (black), neutrons emission rate (green), MHD energy (cyan), D- $\alpha$  signal (violet). The dashed line marks the beginning of the ITB loss.

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- $\alpha$  signal. (Figures 1 and 4 at  $t \sim 1.02$  s). Unfortunately, measurements of the safety factor profile were not available for these discharges.



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,  $\alpha$  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.

## References

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