Power modulation experiments in JET ITB plasmas

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Power modulation experiments are a well known tool to investigate electron heat transport and have been widely used in conventional L-mode or H-mode plasmas. In this paper new results are presented of power modulation experiments in JET plasmas characterized by strong electron and ion Internal Transport Barriers (ITB).

The modulated power source is RF ICRH power in mode conversion scheme, which takes place in D plasmas with ^{3}He concentrations of 10-20%[1,2]. This provides a source of direct, localized and controllable power to electrons, suitable for transport studies of electron ITBs. The ECE diagnostic allows time and space resolved measurements of the T_e perturbation. 3.25-3.6 T, 2.6-2.9 MA plasmas with n_{eo}~3-5$10^{19}$m^{-3} have been used. LH preheat (2-3 MW) was applied to achieve configurations with deeply reversed magnetic shear (s). The ITB is located in the region of negative s. Up to 18 MW of NBI power and 4 MW of ICRH power modulated with half depth at 15-45 Hz with duty cycle ~60% were applied. The MC power has been localized either at the ITB layer, providing a heat wave generated in the ITB region, or just outside it, providing a heat wave that travels towards the ITB. The ITB is mainly sustained by NBI power, but when the RF is deposited inside the ITB radius, the good localization of power allows to reach outstanding plasma performance, with T_{i0}~24 keV, T_{e0}~13 keV, n_{e0}~5 10^{19} m^{-3}, at an additional total power level of 15 MW. The equivalent Q_{DT} is estimated to be ~0.25 in these discharges.

Experimental Results

Two RF deposition schemes have been explored: a) ^{3}He concentration ~12% (mixed minority heating and mode conversion), which led to the best ITB performance; b) ^{3}He concentration ~20% (full mode conversion regime), which allowed the best transport studies. Figs.1 and 2 show steady-state profiles of T_e, T_i, n_e, q and profiles of amplitudes (A) and phases (φ) at 1st harmonic of the T_e heat wave obtained by standard FFT techniques. Fig.1 refers to one case of type a) in which the MC power was located in the ITB layer; the heat wave is then travelling in two directions away from the ITB. Fig.2 refers to a case of type b) in which the MC was located just outside the (weaker) ITB. Note that in this case a fraction of the power is also deposited to electrons in the centre via fast wave Landau damping, so there are two heat waves propagating towards the ITB, one from the centre and one from the outer region.

Maximum care needs to be taken when performing the FFT analysis of T_e modulation data to derive profiles of A and φ. In fact an intense MHD activity is often present in these plasmas, with frequent crashes due to internal kink modes (typically m=2, n=1). These crashes if included in the analyzed time interval generate a broad low frequency spectrum (0-25 Hz) which is peaked in space at the ITB radius and pollutes the real heat wave signal.

Only data exhibiting in the T_e frequency spectrum a clear peak at the modulation frequency well above the continuum background have been retained in this paper and for the modelling work.

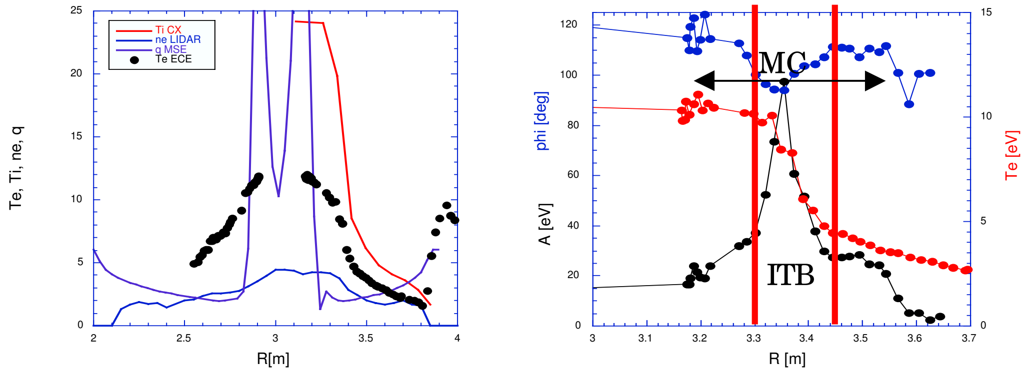

Figure 1 *a) Experimental profiles at t=48 s (maximum performance) of electron and ion temperatures, density and safety factor for shot 59397 (3.45T/2.8 MA, ^{3}He concentration ~12%, ICRH f=33 MHz). b) profiles of T_e (red), amplitude (black) and phase (blue) at 1st harmonic of the modulation frequency (15 Hz) during the time interval 46.2-46.48 s. Mode converted modulated RF power is applied at the ITB location.*

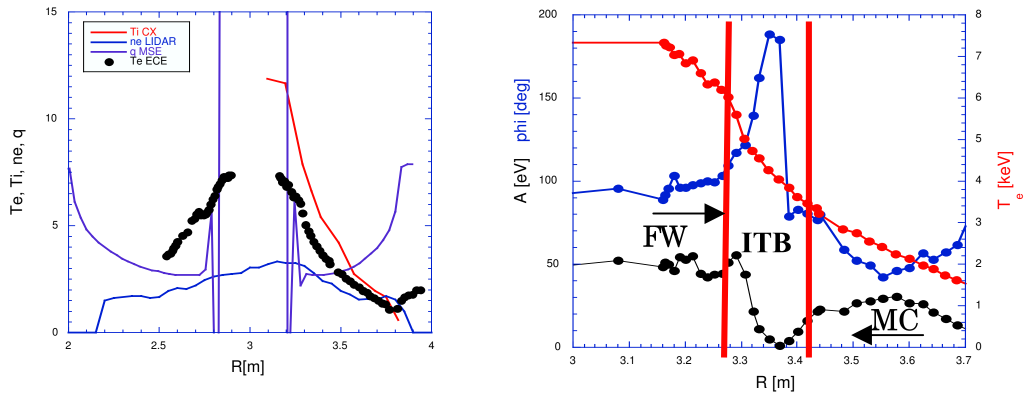

Figure 2 *a) Experimental profiles at t=45.5 s of electron and ion temperatures, density and safety factor for shot 62077 (3.25T/2.6 MA, ^{3}He concentration ~20%, ICRH f=37 MHz). b) profiles of T_e (red), amplitude (black) and phase (blue) at 1st harmonic of the modulation frequency (20 Hz) during the time interval 45.5-45.7 s. Mode converted modulated RF power is applied outside the ITB location.*

Fig.2 is particularly interesting because it shows that the heat wave is strongly damped when meeting the ITB from either side, implying that ITBs are narrow layers of very low heat diffusivity (χ_e). In addition, it shows that χ_e is not uniform inside the ITB: looking at the slopes of A and φ, one can see that the inner part has lower χ_e, i.e. a stronger stabilization of turbulence. The outer part shows reduced χ_e compared to outside ITB, but still higher than in the inner ITB region. This could correspond to partial stabilization. This observation is in agreement with earlier perturbative studies of JET ITBs using cold pulses from the edge [3]. The cold pulse showed a growth when meeting the ITB foot (corresponding to transport re-enhanced in the more fragile outer ITB part) and then a strong damping further inside. The latter result was also reproduced by turbulence simulations [4]. On the other hand, no sign of amplification of the heat wave when it meets the ITB foot is observed, consistent with the picture of an erosion of the ITB by cold pulses due to increased temperature gradient associated with the cold wave.

Modelling modulation data

Attempts to model these experimental results are in progress. Unlike the case of cold pulses, unfortunately turbulence simulations are not feasible for a modulation experiment at 15-45 Hz due to the long time intervals that it would be necessary to cover. The situation of first principle 1D models like the Weiland [5] and GLF23 [6] models is not satisfactory at all. In fact the Weiland model does not contain the $s<0$ stabilization mechanism that seems to play a crucial role in JET reverse shear ITBs [7]. On the other hand, also attempts to model the results using GLF23 did not succeed in reproducing the ITB location and strength in first place, so no meaningful comparison with the modulation results was possible.

Empirical models have therefore mainly been used. Basically two types of empirical models were employed: either a simple constant χ_e profile with a “hole” at the ITB location as illustrated in Fig.3a and 4a, or the critical gradient model presented in [4,8], featuring an increase of turbulent transport above a critical value of the inverse temperature gradient length R/L_{Te}:

$$\chi_e = \chi_s \mathrm{q}^{1.5}\,\frac{T_e}{eB}\frac{\rho_s}{R}\left(\frac{-R\partial_r T_e}{T_e}-\kappa_c\right)H\left(\frac{-R\partial_r T_e}{T_e}-\kappa_c\right)+\chi_0 \mathrm{q}^{1.5}\,\frac{T_e}{eB}\frac{\rho_s}{R} \qquad (1)$$

where $\rho_s = \sqrt{m_i T_e}\,/eB$, q is the safety factor, χ_0 and χ_s are dimensionless numbers giving respectively the residual and turbulent transport assuming a gyro-Bohm normalization, κ_c is the threshold, which was assumed higher in the ITB layer than in the rest of the plasma in order to suppress the turbulent contribution to χ_e . Figs.3 and 4 illustrate the results of the simulations of 59397 and 62077 using the simple constant χ_e model.

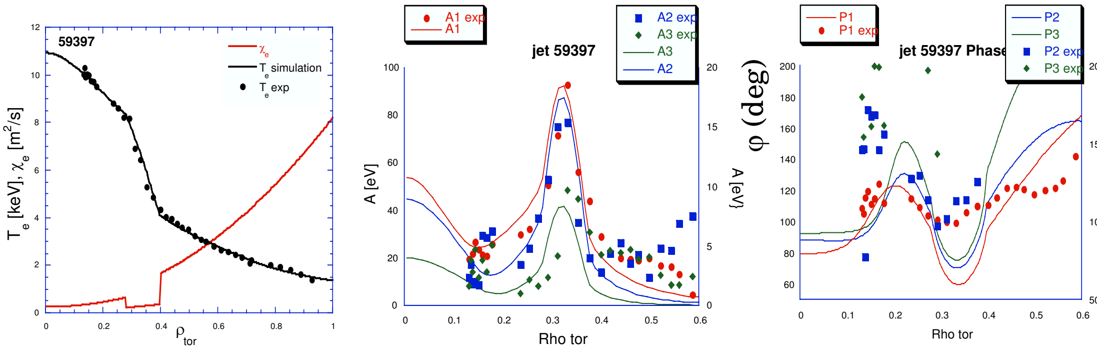

Figure 3. *Experimental (dots) and simulated (lines) profiles of a) T_e, b) amplitudes and c) phases at 3 harmonic for shot 59397. In a) also the (constant) χ_e profile used in the simulation is plotted.*

In the case of deposition at the ITB (Fig.3), provided a rather narrow deposition profile is used for the MC deposition, the agreement with T_e and A is reasonably good at all harmonics, but the modelled phases are significantly lower than the experimental one. Modelling with the empirical gradient model of Eq.(1) did not yield significant improvement in the reproduction of data. Other possible spurious effects besides MHD crashes effects have been explored. Modulation of the Shafranov shift was shown to affect the amplitude peak by 10-15 eV at most. Modulation of the location of the ITB boundaries or of the depth of the χ_e reduction were shown not to play an important role as they would generate features that are not seen in the data. However, modelling modulation data of shots of similar type but with higher modulation frequency generally results in better agreement also with phase profiles, suggesting the discrepancy with the simulation at lower frequencies may come from some low frequency non-diffusive contribution to the heat wave propagation , including still the possibility of remaining MHD activity contamination, which may be particularly nasty in these cases where the RF power is deposited in the ITB layer.

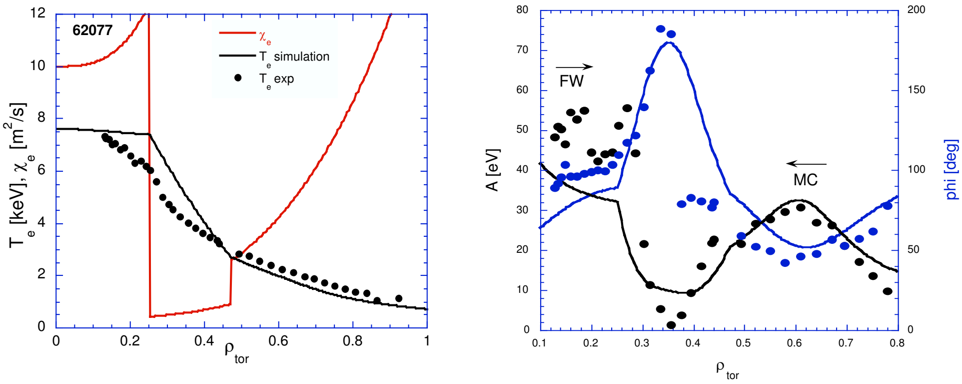

Figure 4. *Experimental (dots) and simulated (lines) profiles of a) T_e, b) amplitudes and c) phases at 1st harmonic for shot 62077. In a) also the (constant) χ_e profile used in the simulation is plotted.*

Matching the phase values does not instead seem a problem in the case of propagation towards the ITB (Fig.4). Of course the simple model used in Fig.4 is not able to fully account for the physics involved, in particular the variation of χ_e within the ITB which is also required to match the T_e profile shape and which may result from a threshold profile increasing towards the inner ITB part due to magnetic shear becoming progressively more negative. However even this simple model is capable of reproducing the gross experimental evidence. We expect that a finer reproduction of the experimental features will come from simulations that are in progress using the critical gradient model with a properly shaped threshold profile.

Conclusions

For the first time T_e modulation experiments in plasmas characterized by strong ion and electron ITBs in configurations with reversed q profile have been performed. Modulated RF power was located either at the ITB location or just outside it. The ITB behaves as a narrow layer of reduced heat diffusivity which stops rapidly the heat wave propagation. The ITB inner part appears characterized by best stabilized turbulence and lower χ_ε. The outer ITB part has higher $\chi_{\varepsilon\, e}$ and is more fragile. Modelling these results with either empirical or first principle transport models is in progress and preliminary results have been presented.

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